STAFFORD, JORDAN W., M.S. Effect of Fatigue on Postural Control (2018).
Directed by Dr. Christopher K. Rhea. 80pp.

Postural control is a complex and dynamic process that is further complicated by ever changing individual characteristics and environmental factors. For example, even when attempting the simple task of standing still, the postural control system must adjust the body to account for internal (e.g., respiration) and external (e.g., gravity) perturbations. These postural adjustments can be more difficult if fatigue is present, which can delay the timing or reduce the magnitude of the postural adjustment. However, the extent to which fatigue influences postural control is not well understood. This is a challenge because balance tests are becoming more commonly adopted in the civilian and military athletic communities to characterize neuromotor control after head trauma or other neurological changes. Thus, there is a need to better understand how fatigue effects performance in a variety of postural control tasks in order to better interpret data from these balance tests. The purpose of this study was to measure postural control with objective balance assessments before and after a standardized fatigue protocol. It was hypothesized that (1) a decline in postural control would be observed immediately after the fatigue protocol, but would return to baseline levels after 9 minutes and (2) the magnitude of the immediate postural control decline would be associated with an individual's level of perceived fatigue.

Hypothesis one was partially supported, as the BtrackS Balance Test was affected acutely after fatigue, $F(2.36,58.95) = 6.07$, p = .003, partial $\eta^2 = .195$, while AccWalker showed no changes after fatigue. For hypothesis two, the only significant association

between the change in perceived fatigue and the change in postural control was between the NASA-TLX and AccWalker thigh flexion SD in the head shake condition, $r_s(25)=.492$, $p = .012$. These findings will help clinicians working with civilian and military athletic communities select the test most appropriate for them based on their desired assessment characteristics (static or dynamic balance) and administration time relative to physical exertion.

EFFECT OF FATIGUE ON POSTURAL CONTROL

by

Jordan W. Stafford

A Thesis Submitted to
the Faculty of The Graduate School at
The University of North Carolina at Greensboro
in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Greensboro
2018

Approved by

____

Committee Chair

APPROVAL PAGE

This thesis written by Jordan W. Stafford has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

Committee Chair ______________________________

Committee Members ______________________________

____

____

____
Date of Acceptance by Committee

____
Date of Final Oral Examination

TABLE OF CONTENTS

CHAPTER I

INTRODUCTION

Postural control is defined as the ability to maintain upright stance, which is accomplished through the integration of internal and external forces and environmental factors (Yaggie & McGregor, 2002). Postural control is a dynamic activity with multiple governing systems that change with the environment and individuals (Winter, Patla, & Frank, 2010; Oie et al., 2002). Within the nervous system, information from the vision, proprioception, and the vestibular systems all play a role in keeping a person upright. Individual factors that can affect postural control are age, sex, and fatigue. It is well known that fatigue can affect motor behavior, and some research has examined how fatigue effects static balance and gait tasks. However, the majority of balance and gait testing has been done on participants in a non-fatigued state, which may not fully characterize more clinical and/or real-world situations for which the tests have been developed.

Currently there is no consensus for the best way to measure fatigue. Rate of perceived exertion (RPE) is the subject's subjective, or perceived feeling of fatigue. This is typically measured during or after physical exertion. Many factors can influence RPE such as gender, type of activity, and the environment. Nevertheless, RPE was found to be a reliable measure of fatigue (Chen, Fan, & Moe, 2002). Fatigue can also be defined in strictly a physical sense—the loss of force in muscular contraction (Saladin, 2012;

Vuillerme, Nougier, & Prieur, 2001)—or it can be combined with mental stress and quantified using the NASA-TLX (Hart, 2006).

Fatigue can be local or whole body, both of which are dependent on the exercise intensity, duration, and an individual's physiological response to exercise. Local fatigue refers to the fatiguing of a particular muscle or muscle group. Alternatively, whole-body fatigue refers to the fatiguing of more than one muscle or muscle group. Both local and whole-body fatigue effects can cause changes in postural control once a threshold is crossed. In particular, research has shown that local fatigue begins to effect postural control when maximal voluntary contraction has been reduced by 25-30% (Paillard, 2012). Whole body fatigue is more difficult to quantify, so postural control deficits after precise measurements of whole body fatigue currently do not exist.

At present the relationship between fatigue and postural control is not well understood. This may result in fatigue affects being under- or over-emphasized in postural control literature, which is a challenge because balance tests are becoming more commonly adopted in the civilian and military communities to characterize neuromotor control after head trauma or other neurological changes. Thus, there is a need to better understand how fatigue effects performance in a variety of postural control tasks in order to better interpret data from these balance tests.

The purpose of this study was to measure postural control with objective balance assessments before and after a standardized fatigue protocol. It was hypothesized that (1) a decline in postural control would be observed immediately after the fatigue protocol, but return to baseline levels after 9 minutes and (2) the magnitude of the immediate postural control decline would be associated with an individual's level of fatigue.

CHAPTER II

REVIEW OF LITERATURE

Overview

The first part of this section reviews relevant literature examining human postural control, how it is measured, neurosensory systems that contribute to postural control, and how postural control may be compromised due to a neurological insult or natural aging. The second part of this literature review focuses on the central thesis of this project by describing the concept of fatigue, how fatigue is measured, localized versus whole body fatigue, the functional role of fatigue on performance and injury risk in high performance athletes and military populations, postural control compensatory strategies after fatigue, and the current gaps in the literature relative to postural control and fatigue.

Postural Control in Humans

Postural control is necessary to complete nearly all human activities. However, it is a complex and dynamic process due to the structure of the human body. With approximately two-thirds of our body mass located above the trunk, we are not inherently stable (Winter, 1990). This is advantageous, as it allows humans to move throughout the environment without the need to overcome significant inertia. On the other hand, too much instability is problematic, as it can increase the risk of a fall and/or injury. To help control posture, humans' multiple systems (e.g., vision, vestibular, proprioception), which can be reweighted if needed, that help keep us upright (Winter, et al., 2010; Oie et al., 2002). This dynamic support system is what allows us to turn our heads while walking or step into a dark room without losing postural control. Combined with the dynamic nature of movements such as walking this makes the description and measurement of postural control complex.

It is also important to acknowledge that the goal of postural control is task-dependent. When standing still, the goal is to keep the CoM within the stationary base of support BoS. Engaging in non-stationary tasks, such as walking, requires the BoS is moving while the CoM is constantly moving in and out of the BoS. Thus, postural control in dynamic tasks requires coordination of the CoM and BoS such that the CoM can be corralled by the BoS before the loss of upright stance. Dynamic postural control is required in many real-world tasks and failure to adequately control posture on this context could lead to increased fall-risk. Thus, dynamic postural control is also commonly called functional balance and gait (Berg & Norman, 1996).

Measurements of Postural Control

Postural control is a general concept that can be measured objectively or subjectively. Objective measurement refers to quantifying postural control via a sensor—commonly a force plate, inertial sensor, accelerometer—that provides a reliable and valid assessment of movement as long as the sensor is calibrated. This type of measurement is typically done in a laboratory setting where the environment is controlled and there is ample time, financial, and human resources to complete this type of testing. In a clinical setting, the same resources are sometimes not available, leading to the need to use subjective assessments of postural control. Both types of postural control assessment have pros and cons, which are further explored in the following sub-sections.

Objective Assessment of Postural Control

Force Plate Assessment

One of the most common ways to objectively assess postural control is by measuring the displacement and/or velocity of the CoP over time, which is typically recorded with a force plate. It is impossible for a human to stand perfectly still because they are constantly responding to internal (e.g., breathing) and external (e.g., gravity) disturbances. The postural control response is ideally scaled to the disturbance in order to maintain upright stance (Rietdyk, Patla, Winter, Ishac, & Little, 1999; Adkin, Frank, Carpenter, & Peysar, 2000). However, a compromised postural control system exhibits delayed timing and/or reduced magnitude in its response to the disturbance (Claudino, dos Santos, & Santos, 2013; Gago, Yelshyna, Bicho, Silva, Rocha, Rodrigues, & Sousa, 2016). Thus, movement of CoP is commonly used as a window into postural control, with more CoP movement typically interpreted as relatively worse postural control. CoP measurement using a force plate was typically done in a controlled laboratory setting due to the need to have a level and non-vibrating surface. However, recent advancements in technology have allowed for the development of portable force plates design for testing in the field. One such device is called the Balance Tracking System (BTrackS; Chang, Levy, Seay, & Goble, 2014), which has been shown to have appropriate clinical sensitivity to assess postural control after a concussion (Goble, Manyak, Abdenour, Rauh, & Baweja, 2016), as well as an reliable measurement of postural control after fatigue (Benedict, Hinshaw, Byron-fields, Baweja, & Goble, 2017).

Movement of the CoP can be quantified in a number of different ways. A force plate measures CoP displacement in the anterior-poster (AP) and medial-lateral (ML) directions over time, which can be used to examine postural control differences between different groups and/or medical/experimental conditions (Sefton, Hicks-Little, Hubbard, Clemens, Yengo, Koceja, & Cordova, 2009; Marigold, & Eng, 2006; Claudino, dos, & Santos, 2013). It is also common to take the first derivative of the displacement time series to get a velocity time series, which has been used to investigate postural control after a concussion (Powers, Kalmar, & Cinelli, 2014; Slobounov, Cao, Sebastianelli, Slobounov, & Newell, 2008), during natural development (Palluel, Nougier, & Olivier, 2010; Riach, & Starkes, 1994), or to help identify fall-risk in older adults (Costa, Priplata, Lipsitz, Wu, Huang, Goldberger, & Peng, 2007; Melzer, Benjuya, & Kaplanski, 2004). While CoP displacement has been shown to be useful, CoP velocity has been suggested to be the variable attended to by the nervous system to help control posture (Delignières, Torre, & Bernard, 2011; Jeka, Kiemel, Creath, Horak, & Peterka, 2004).

Regardless of whether the researcher uses CoP displacement or velocity, a decision of how the time series will be quantified still needs to be made. This is important because postural control is influence by multiple variables inside and outside the body; and controlled by both multiple and varying systems within the body. The method used to quantify a time-series must be specified in order to discern what factors are influencing certain characteristics of postural sway.

Mean of the CoP velocity, standard deviation (SD) of the CoP velocity or displacement, and path length of the CoP displacement are among the more common linear metrics used to evaluate postural sway data (Cavanaugh, Guskiewicz, & Stergiou, 2005). These metrics are useful because they provide a summary of the overall movement of the CoP during the balance test, which can provide insight into postural control. However, using a summary metric ignores the time-evolving nature of the displacement or velocity time series. To address this characteristic, nonlinear metrics have been used to evaluate postural control. The nonlinear framework is based on the idea that postural control is governed by the interaction of physiological systems in the individual, task demands, and environmental conditions (Cavanaugh et al., 2005). Nonlinear systems are organized based on initial conditions and rules governing interactions among systems. Due to the multiple interactions possible, there is not a simple input-output relationship as seen in linear models. Because nonlinear systems evaluate variability over time, there is a longer time scale required for collection to determine postural movement patterns. One of the most common nonlinear metrics to examine postural control is entropy (Cavanaugh et al., 2006; Manor et al., 2010; Ramdani, Seigle, Lagarde, Bouchara, & Bernard, 2009; Rhea et al., 2011; Stins, Michielsen, Roerdink, & Beek, 2009).

Smartphone Assessment

Smartphones have become a popular way to measure postural control in recent years (Patterson, Amick, Thummar, & Rogers, 2014; Patterson, Amick, Pandya, Hakansson, & Jorgensen, 2014; Rehan, & Gumaa, 2017; Rhea et al., 2017). This is due to the relative ease to administrate the tests with custom designed smartphone apps, as well as the lost-cost associated with this technology. However, there has been a call for the careful implementation of such devices to ensure the clinical utility has been carefully tested and the app has been shown to have appropriate reliability and validity (Boulos, Brewer, Karimkhani, Buller, & Dellavalle, 2014). Two apps to measure postural control current meet this criterion. Sway Medical devised an app that measures static postural control while a participate stands with their eyes closes (Patterson, Amick, Thummar, & Rogers, 2014; Patterson, Amick, Pandya, Hakansson, & Jorgensen, 2014). While useful, static posture tasks can mask neuromotor dysfunction in some cases due to their relatively low task difficulty (Baloh et al., 1994). To address this challenge, Rhea and colleagues recently developed an app that uses a dynamic postural control test, which has been shown to be a reliable and valid way to measure postural control (Kuznetsov et al. 2018), as well as having clinical utility in sub-concussed and concussed populations (Rhea, Kuznetsov, Robins, et al.,2017; Rhea, Kuznetsov, Ross et al., 2017).

Subjective Assessment of Postural Control

A recent emphasis on subjective assessments of postural control came from a need to diagnose a concussion, which has no physical changes in the brain; even with modern imaging techniques such as fMRI. Only functional changes in the brain that result can help to diagnose a concussion (Broglio, Guskiewicz, & Norwig, 2017). The earliest subjective measures in concussion screening were vague and non-specific; such as asking a patient “how many fingers they could see.” More recently in 1982 the Sports as a Laboratory Assessment Model (SLAM) became a widely used checklist for common symptoms such as nausea, headache, dizziness, and memory problems. SLAM and other subjective measures were an improvement, but still relied heavily on the patient or athlete being both honest and understanding how to quantify the level of a symptom. This makes subjective assessment limited in reliability of measuring symptoms (Broglio et al., 2017; Cavanaugh, Guskiewicz, & Stergiou, 2006). Studies done recently have also showed that these symptoms are commonly reported in both concussed and non-concussed athletes (Broglio et al., 2017). Convoluted results are more common in athletic populations where an athlete may sustain an impact to the head and have a headache that may be the result of a non- concussion etiology. The currently accepted subjective concussion assessment is the Balance Error Scoring System (BESS), which was validated against a force plate, an objective assessment tool (Riemann, Guskiewicz, & Shields, 1999). While still subjective it does allow the changes in postural control that result from a concussion to be measured with minimal equipment and fairly quickly. While there have been a number of subjective assessments of postural control developed for a variety of clinical population, the three most common are the Berg Balance Scale (BBS), Community Balance & Mobility (CB&M) Scale, and the BESS—all of which are reviewed in the following section.

Berg Balance Scale (BBS)

The BBS was first developed to evaluate elderly patients with neurological conditions. Currently it is commonly used in clinical settings to evaluate posture in patients with various conditions that might affect posture (Berg, Wood-Dauphinee, & Williams, 1995). The BBS consists of 14-items rated from 0-4. Movements include static stance, tandem stance, and picking up an object from the floor. Studies have shown the

BBS to be reliable and valid for evaluating postural control in stroke and elderly populations (Berg et al., 1995).

Community Balance and Mobility (CB&M) Scale

The CB&M is a 13-item 6-point scale originally used to measure rehabilitation progress of TBI patients (Inness et al, 2011). Tasks on the CB&M include: tandem walking, running with an abrupt stop, transitioning from forward to backward walking and walking while looking to the side. The CB&M is often administered after a patient can stand and walk unassisted but may not be fully ambulatory. The tasks are meant to mimic those necessary for functioning in a community (Inness et al, 2011).

Balance Error Scoring System (BESS)

The BESS test is one of the most commonly used diagnostic tool for concussion in sports. Originally it was developed as a feasible cost-effective way to test balance on multiple surfaces. The BESS consists of standing in dual-stance, single-stance, and tandem-stance on a hard and foam surface for 20 seconds each with eyes closed while the administrator counts the number of times a person makes any of the following errors: (1) moves hands off the hips, (2) opens the eyes, (3) takes a step, stumble, or fall, (4) abducts or flexes the hip beyond 30 degrees, (5) lifts the forefoot or heel off the testing surface, or (6) remains out of the initial testing position for more than 5 seconds. The total number of errors are tallied, which is considered the BESS score. The BESS has since been modified (M-BESS), which removed the foam surface from the test, allowing for the administration of the M-BESS with no equipment, which is useful in many clinical settings.

What is considered a normal score on the BESS is primarily dependent on age. BESS scores tend to decrease (increase in number of errors) with increasing age, with a significant drop after age 60 (Iverson & Koehle, 2013). BESS scores are divided into six categories based on the number of errors counted by the test administrator. Scores range from very poor (24+) to superior (0-5) for age 29 and below; ages 65-69 are rated 39+ and 0-12 respectively. BMI has also been shown to effect BESS test results for women more so than men. Test of obese men and women showed more poor BESS scores for obese women compared to their lower BMI counterparts (Iverson & Koehle, 2013).

While the BESS has been widely used in many clinical settings, its reliability has been called into question (Finnoff, Peterson, Hollman & Smith, 2009). This arises from challenges associated with subjective assessment, as within- and between-person and session assessments may change due to human error and/or training. Moreover, the environment (Rahn, Munkasy, Joyner, & Buckley, 2015) and fatigue (Benedict et al., 2017) can influence the BESS. Thus, while the BESS is still a widely used tool, objective assessment of postural control has been suggested to be a stronger tool for the profession to adopt moving forward given the development of more portable and cost-effective sensors (Broglio et al.,2017).

Neurosensory Systems Contributing to Postural Control

Vision, vestibular, and somatosensory systems have been shown to be the primary controls to maintain posture. It has been shown that the ability to stay upright peaks in the adolescent years and gradually declines until around age 60 (Gaerlan et al., 2011). Each system contributes to upright posture by giving feedback that allows for the appropriate corrective torques to both internal and external perturbations (Peterka, 2002). The manner in which each system contributes to posture changes with time and circumstance. It was demonstrated that as we age or become fatigued there are significant changes in the feedback and control systems associated with posture.

With age, fatigue, or other factors interacting in a dynamic way, humans sometimes have degraded neurosensory systems giving feedback. According to Peterka (2002) there is a shift in the weighting of information from one system to another as one system becomes perturbed. Vestibular cues increase as visual perturbations increase and vice versa, in a healthy population. However, data showed that while systems can compensate for each other there is a constant corrective torque that seeks to maintain posture but also dynamic behavior independent of sensory information (Peterka, 2002). This is presumably so the body is prepared for another perturbation that has not yet occurred. That is, there is no equilibrium for posture even in quiet stance, which partially explains why linear models do not account for all postural variability (Cavanaugh et al., 2005).

Vision System

While vision is generally the primary controller of posture, it is important to understand that the CNS gives different weights to how much each system contributes to postural control. Changes in which system is controlling posture represent changes in postural sway on various measurement devices such as forces plates. Changes in maintaining postural sway as stimuli to the CNS change is known as sensory re-weighting (Oie, Kiemel, Jeka, 2002). Research shows that there is a graded response to stimulus changes to maintain posture. The 2002 study by Oie et al. used visual and somatosensory stimuli to measure changes in subject postural control. Stimuli were either static or dynamic and given at different frequencies. Subject response was stronger when both stimuli were dynamic rather than one dynamic and one static.

An important consideration is that in the real-world people are often presented with one change in input that is not matched by another sensory input. Oie et al. use the example of a traffic light. When the light changes, cars begin to move across the visual field. The CNS interpret this as a change from a static to dynamic visual environment. This change in visual environment is not accompanied by a change in vestibular or proprioceptive stimulation. In this situation, the nervous system will reduce the weight, and response, given to visual stimulation and increase response to other sensory systems to maintain balance. In summary, as the motion of the environment increases, vision becomes a less reliable indicator of posture and the body decreases weight given to vision in maintaining posture.

In 2012 a study done on 194 adults in their 20s and 30s showed that vision is the primary system used in balance during young adulthood. Within the visual system are three subsystems that contribute to balance and posture. First, the central of focal system specializes in motion perception of an object outside the body. Second, the peripheral vision is more sensitive to movement of the environment and is thought to dominate in both perception of self-motion and postural control (Gaerlan, Alpert, Cross, Louis, & Kowalski, 2012). Last, the retinal slip is part of afferent motion perception and “is related to person's displacement by the central nervous system (CNS), and is used as feedback for compensatory sway" (Guerraz & Bronstein, 2008).

It is noted by Gaerlan et al., that with age the contribution of each system may change. The different systems also contribute in changing proportions in changing circumstances as given in more detail later. A good example is that most healthy people can still stand upright in a dark room. This study showed a threefold increase in trunk sway when subjects had their eyes closed, but none lost their balance.

Vestibular System

While the visual system is the primary contributor to balance the vestibular system provides the most complex contribution. In the role of postural control, the vestibular system can be seen as the intersection between systems. The vestibular system is multisensory and, therefore, is difficult to clearly distinguish from the visual and proprioceptive systems. Visual and proprioceptive systems interact with the vestibular system throughout the central vestibular pathways and are essential for gaze and maintaining posture (Gaerlan et al., 2011). The vestibular system acts as a cross roads contributing to both input and output of balance. "Both visual and proprioceptive systems interact with the vestibular system throughout the central vestibular pathways and are essential for gaze and postural control" (Gaerlan et al., 2011).

Proprioception System

Primarily responsible for the body's position in space the proprioception system uses muscles spindles that play a key role in balance. Mechanoreceptors provide information to the nervous system about the length of the muscle and the velocity of a contraction. This is how people are able to know what their muscles and joints are doing without seeing them in space. The Golgi-tendon organ which is located at the muscle-tendon transition point relays information about tensile forces to the nervous system. Once the Golgi-tendon is activated, information is relayed via afferent neurons synapse with spinal cord interneurons; resulting in decreased tension in muscle and tendon.

It is presented in the 2011 study by Gaerlan et al. that young adults have demonstrated strategies to maintain balance when vision is obstructed. Proprioception is thought to be the more frequently used system to compensate in these circumstances. This may partially explain while balance decreases with age and increase balance with exercise. Increased age leads to slower muscle activation and subsequent muscle signaling, leading to a decreased in the ability of the proprioception system to contribute to balance. The reverse occurs with exercise, at any age, increase neuromuscular firing leads to increased balance with exercise. This directly relates to how open and closed loop systems change as we age.

The immediate effect of muscle fatigue is a decrease in the proprioceptive abilities of muscles (Vuillerme, Nougier, & Prieur, 2001). The negative effects of fatigue are thought to be brought on by lack of proprioception through deficiencies of activation in mechanoreceptors. In this case fatigue is defined by the inability to produce an expected movement or force. This fatigue occurs daily due to normal activities and the CNS compensates for this muscle fatigue often using the visual system. In 2001, Vuillerme et al. showed that in a fatigued condition, subjects stood barefoot on their toes until volitional fatigue was reached, an average of 14 minutes on the first trial to three minutes on the last trial, subjects were able to compensate using vision to maintain posture. When vision was removed subjects were less able to maintain posture which relied on depressed proprioceptive cues. This agrees with the writing by Oie et al. that showed postural response was stronger when two dynamic stimuli were introduced to the subject's environment.

In conclusion, there are many variables that affect how the CNS maintains posture in different environment and among different groups. Studies show that elderly are more likely to lose balance in any condition and especially when two sensory systems are altered or removed (Oie et al., 2002). Other populations such as those who have suffered a concussion or TBI will have different re-weighting and compensatory strategies to maintain posture. By comparison, studies investigating the effects of concussion on CoP displacement have shown increased anterior-posterior CoP displacement in collegiate student athletes who suffered a concussion. Affects were seen over 30 days after injury and appeared to have resolved 6-months after injury (Slobounov et al., 2008). Other studies that investigated approximate entropy (ApEn) associated CoP displacement post-concussion showed that those who suffered a concussion had decreased medio-lateral ApEn and increased medio-lateral ApEn (Sosonoff et al., 2008). While aging is a primary factor studied in postural control and is discussed more later it is critical to consider the sample being used in a study for posture due to change mechanisms used to control posture in different populations. Abnormal levels of postural sway have been seen in stroke and traumatic brain injury patients, symptomatic elderly fallers, and children with developmental disorders.

Measuring the Neurosensory Contributions to Postural Control

Neurocom Sensory Organization Test (SOT) was developed in order to parse out differences in how perturbations in each system can affect postural sway (Pletcher et al., 2017). During the test, a patient is placed inside the Neurocom SOT which isolates there vestibular, visual, and proprioceptive systems to a controlled environment. While standing on a force plate each system is perturbed. The environment will “move” or the floor will tilt in a direction forcing the patient’s postural control systems to compensate. The force plate then measures output via postural sway. This allows for the isolation of the contribution of each postural control system. By extension, after neurological insult symptoms can be used to infer affected postural control system via a Neurocom SOT (Pletcher et al., 2017).

Changes in Postural Control

Neurological insult, natural aging, and fatigue can impact postural control in different ways. Natural aging leads to increase fall risk but research indicates there is no significant difference in overall postural sway between younger and older individuals (Bird, Pittaway, Cuisick, Rattray, & Ahuja, 2013; National Council on Ageing 2005). Indicating that the cause of increased fall risk is more complex than just increased postural sway. Neurological insult such as concussion or TBI is perhaps the most complex set of effects on postural control due to the cascade of symptoms that result from such an injury. Athletes who have suffered a concussion are often diagnosed using a BESS test that has only limited reliability (Guskiewicz, Ross, & Marshall, 2001; Goble, Manyak, Abdenour, Rauh, & Baweja, 2016). Additionally, increased postural sway has been shown to linger after BESS scores have returned to normal and the athlete is considered able to return to play despite increased fall risk (Slobounov, Cao, Sebastianelli, Slobounov, & Newell, 2008). Fatigue has been shown to increase postural sway in different ways depending on the individual, the type of fatigue, and joint location compared to center of gravity. Paillard (2012) showed that fatigue induced by a running activity must exceed 60% of the subjects maximal HR in order to induce changes in postural sway. Other factors such as hydration, length of exercise, and movement within a task have been shown to effect postural sway (Paillard, 2012).

Neurological Insult

Neurological insults are defined as trauma to the head that lead to changes in brain functioning. These are commonly classified as mild, moderate, or severe traumatic brain injuries. A concussion is defined as a mild traumatic brain injury by The National Institute of Health and is considered a major public disorder. It has been estimated that 23% of active-duty military personnel in Iraq and Afghanistan have suffered a concussion (Buckley, Oldham & Caccese, 2016). In addition to the annual cost of 22 billion for combined civilian and military concussion there is the risk of second impact syndrome, an impact after the initial concussive blow that occurs before the resolution of the neurometabolic cascade set off by the initial impact. The diagnosis of a concussion is complex under ideal circumstances. Diagnosis becomes further complicated the more removed from a controlled lab setting the subject gets. In an effort to improve the accuracy and reduce the time it takes to diagnose a concussion, methods have been developed to diagnose concussions based on symptoms.

Changes in postural control are a cardinal symptom of a concussion, so subjective field tests such as the BESS have been adopted (McCrea et al., 2003). However, the BESS has been shown to be only moderately sensitive and there are lingering effects that could result in a second fall or concussion leading to more severe injury. Objective tests of postural control have also been adopted to examine changes in postural control after a neurological insult (Guskiewicz et al., 2016; Cavanaugh et al., 2006). Studies investigating the effects of concussion on COP displacement have shown increased anterior-posterior COP displacement in collegiate student athletes who suffered a concussion. Affects were seen over 30 days after injury and appeared to have resolved 6-months after injury (Slobounov et al., 2008). Other studies that investigated approximate entropy (ApEn) associated COP displacement post-concussion showed that those who suffered a concussion had decreased medio-lateral ApEn and increased medio-lateral ApEn (Sosonoff et al., 2008). Moreover, decreased dynamic stability seen in athletes with a concussion who have been "cleared for competition" when given a dual-task (Fino, 2016), highlighting the need to appropriately challenge the postural control system to fully understand its functional level.

Natural Aging

It is well-documented that fall-risk increases as people age beyond 60 years old (Bird et al., 2005). It is likely that a big factor in the increase in fall risk is a decrease in balance ability. However, an understanding of the mechanisms that cause a decrease in balance are still developing. Research has shown that with greater increases in postural sway, measured using changes in CoP, comes a greater risk of falling (Laughton et al., 2003). Those researchers used CoP movement to compare elderly "fallers" versus "non-fallers" with a younger population. Balance was assessed using the Performance Oriented Balance and Mobility Assessment (POMA). Lower extremity muscle strength was taken using three maximal voluntary isometric contractions for: tibialis anterior, soleus, biceps femoris, and vastus lateralis. A force plate was used to gather CoP movement and velocity. There were no significant differences in postural sway between elderly fallers and non-fallers in either AP or ML directions, for range or standard deviation. There was a significantly greater AP range and standard deviation between elderly fallers and young subjects. Results showed that elderly fallers had significantly greater short-term (AP) movement compared with a younger group. Average scores on the POMA were similar between elderly faller and non-fallers. There was greater ML CoP range and standard deviation for those who scored lower on POMA.

While there were no significant differences in postural sway between fallers, non-fallers, and young subjects the authors do offer possible explanations that agree with papers investigating compensatory mechanisms for fatigue. Increases in muscle activation and co-activation of antagonistic muscle groups in elderly adults compared with younger adults during standing (Laughton et al., 2003). The authors conclude that the increase in short-term postural sway may be due to the increase in muscle activation. It can be inferred from this that while there may have been the same degree of postural sway it required more muscle activation in elderly subjects compared to young. Further, there was no significant difference in quiet standing sway or postural muscle activity between those who were fallers and non-fallers. This indicates that with age balance can be as it can be in younger years but there is a greater energy cost. These conclusions occur with the previously established ideas that both the elderly and those who have suffered a traumatic brain injury tend to walk and stand in a more flexed and rigid manor.

One limitation to the study by Laughton et al. (2003) is that there was no significant difference between in clinical balance performance, assessed via the POMA. Meaning that only a self-report of fall history classified fallers versus non-fallers. This makes it hard to quantify a difference between the groups. Potentially, this means the POMA was not a valid measure of balance for this study. It is worth noting that the data showed a significantly greater ML direction sway in those who had worse POMA scores.

Fatigue

While a neurological insult or natural aging can influence postural control, so too can fatigue. While there is no consensus for defining fatigue, Saladin (2012) uses it in a strictly physical sense. Fatigue is the progressive weakness and loss of contractility that results from use of muscles. Similar to the Vuillerme et al. (2001) definition of fatigue being an inability to produce and expected force. Workload can be looked at as encompassing the physical and mental aspects of fatigue described by Saladin and Vuillerme et al. (2001) As stated previously the complexity of a task can also affect how fatiguing it is, meaning that accounting for the mental requirement and the physical requirement is important. The NASA-TLX, mentioned more later, is a measure of the total workload of a task, combining mental and physical requirements.

Measurements of Fatigue

Whole Body Fatigue

Measurements of whole body fatigue include heart rate, total work done, and rate of perceived exertion (RPE). RPE is the most common method for measuring perceived physiological stress during activity. The most common RPE scale is the Borg from 6-20; with 6 being laying down in bed and 20 being maximal exertion (Borg, 1982). Currently there is no one accepted method of measuring whole body fatigue, all current methods have limitations and known outside moderators.

A meta-analysis conducted in 2002 by Chen et al. that investigated 437 studies to determine the correlation between RPE and various physiological measures; HR, blood lactate, percent of VO2 max (%VO2 max), VO2, ventilation, and respiration rate. Their results showed that RPE had a weighted mean validity coefficient of 0.62 for HR, 0.57 for blood lactate, 0.64 for %VO2 max, 0.63 for VO2, 0.61 for ventilation, and 0.72 for respiration rate. While it is considered reliable, it is important to note that RPE is still considered a measure of the subjects perceived fatigue unlike more quantifiable measures such as those mentioned above.

There are a number of factors that can influence the utility of the RPE scale. First, it was found have higher validity for a more active population compared to less active or sedentary individuals when HR, blood lactate, and VO2 was used as the evaluation criteria (Chen et al, 2002). Second, RPE may be influenced by sex. For blood lactate and RPE, there was a higher validity for females, 0.71, than males, 0.49. VO2 and %VO2 were more valid for males with 0.80 and 0.46, compared to women 0.03 and 0.02

respectively. Contrasting results were found for ventilation and respiration rate; validity coefficient for men was 0.75 and 0.65 while women showed 0.16 and 0.85 respectively. Collectively, these data suggest that RPE is more valid for men than women, and for a more active population compared to a sedentary one. It is worth noting that there was a gender gap in RPE with whole-body fatigue observed by Pincivero et al. in 2009. Results showed that while females performed more work than males in a rowing exercise, they showed a lower level of whole-body fatigue. From this meta-analysis, it is evident that RPE is the most reliable among well-trained male subjects, such as elite athletes or active duty military soldiers.

Local Fatigue

Local fatigue is divided into two categories (Bellew et al., 2009). Central fatigue is a decline in voluntary activation of skeletal muscle after exercise. Peripheral fatigue is associated with slowing contractile time or increase in relaxation time after exercise or activity. From another point of view a muscle can fatigue in an output (central) or input (peripheral) sense (Bellew et al., 2009). In most settings, once a muscle is tired it is a combination of both.

A common method to measure fatigue of a specific muscle group or joint is maximal voluntary contraction (MVC) or percent of MVC. Generally, researchers use a pre-and post-method to look at the effect of exercise on the MVC of a joint or groups of joint. Often a dynamometer is used to measure force output given by a muscle or group of muscles or an EMG measures the electrical activity during a MVC. Volitional failure is often used in the absence of a dynamometer or EMG. This is inexpensive but also requires the subject to give what they feel is the correct amount of effort, often maximal, and that the subject definition of that effort matches what the researcher's data collection requires. There are three common protocols used during a study looking at MVC and force output pre-and post-exercise (Paillard, 2012): 1) repetition of simple segmental movements on the muscle(s) or joint(s) being investigated; knee, ankle, biceps femoris, etc. until a previously established level of strength loss, 2) repeating several simple segmental movements or maintaining an isometric (or dynamic) contraction for an established amount of time, or 3) volitional failure or exhaustion of the subject. After an exercise or fatigue protocol, a post-MVC is taken to determine the amount of strength loss that occurred. Loss is then given in percent change or difference in watts or newtons. In the case of postural control there is often a post-exercise CoP test given to measure the effects of the amount of fatigue on postural measures.

NASA-Task Load Index

The NASA-Task Load Index (NASA-TLX) is a unique measure of fatigue that can be considered to include both localized muscle fatigue, whole-body fatigue, and mental fatigue. NASA-TLX uses six subscales to measure physical, mental, and emotional costs of accomplishing a task; this is known as the "workload" to accomplish a task. Workload is defined as the cost of accomplishing mission requirements for the human participant (Hart, 2006). The six subscales used represent independent clusters of variables that may apply to a task: mental, physical, temporal, frustration, effort, and performance. Each of the six subscale definitions are weighted based on each subject. This is done at the beginning of a study to determine the weight each subject give to the specific definitions. Each subscale is then multiplied by the previously determined weight to give a composite score for individual definitions of workload.

A study done at the NASA-Ames Research Center on 550 studies showed that the benefit of the weighing dimensions of fatigue and work increased sensitivity to relevant variables and decreased between-rater variability (Hart, 2006). The more complex a task the more likely there is to be variability between individuals and how they experience a fatigue protocol. Whole-body tasks such as walking, running, or cycling tend to require more dimensions used in the NASA-TLX, but it can be applied to any fatiguing task. The dimensions were chosen because they define the subjective workload for different subjects performing a variety of tasks, ranging from simple ankle movements to sprinting or a squat-lift. The NASA-TLX provides a reliable and inexpensive way to measure fatigue and workload when performing a task in a variety of settings. Workload measured by NASA-TLX also accounts for the effects of mental work required to accomplish a task. Neuromotor noise causes mental workload to affect the joint steadiness, particularly in proximal joints, involved in posture (Mehta & Agnew, 2014). Thus, a more complex task would have a greater effect on posture than a simple task if all other factors are equal. For example, a subject that is asked to run in multiple directions will have a greater workload than a subject who is asked to run in a straight line over the same amount of time due to the inertia that needs to be overcome when changing direction.

Functional Role of Fatigue

It has been well documented that many ACL tears that result from non-contact falls occur when fatigue levels are higher and balance ability is decreased compared to a non-fatigued state (Johnson et al., 1998). For example, Johnston and colleagues found that many ACL tears that occur in skiing happen during a fall that occurs on the “last run of the day,” after a day of skiing when muscle are fatigued and balance is compromised. The specific impact on balance is affected by the location and type of fatigue, as shown previously.

The importance of studying fatigue and balance is especially apparent in a military population. Due to the nature of many tasks in the military, they are accomplished in a state of some level of fatigue. This makes standard measures of balance in a non-fatigued state, as often done in a clinical setting, less reliable unless researchers can account for the changes fatigue may cause during a balance test such as the BESS or COP trajectory on a force plate. Whole-body fatigue should be used in the study of military populations since the daily tasks performed do not often involve repeated MVCs such as those used in laboratory studies investigating localized muscle fatigue.

Studies to measure work load and fatigue in soldiers are important for measuring the demands of accomplishing a task. Research looking at walking and running efficiency in both unweighted and weighted conditions is used to measure the demand of traveling a long distance with a pack. This is important due to the frequent marches and hikes elite soldiers are required to perform, often with a weighted back. In 2010, RPE alone was shown to be an accurate measure of workload during a weighted walking or running task in elite British soldiers (Simpson et al., 2010). Soldiers carried a 20kg backpack on a treadmill while HR, oxygen uptake and RPE were recorded. RPE was shown to accurately measure metabolic demand of the backpack carrying task (Simpson et al., 2010). This agrees with previous data shown by Chen et al. (2002) that looked at RPE validity as a measure of physical exertion. It showed that RPE was most accurate for well-trained male populations. Data for the workload of carrying a weighted pack is important to a military population not only due to the frequency that the task occurs but also the unique biomechanics of human walking with a weighted pack on. Walking with a pack is shown to increase forward lean from the pelvis, increasing workload at a greater rate than increasing weight alone (Majumdar, Sudan Pal & Majumdar, 2010).

Measuring fatigue using RPE has been shown to be reliable between both trained and untrained populations (Patton, Morgan & Vogel, 1977). The 1977 study done to compare the RPE and HR of two military populations, fit versus unfit. The fit group had 11% higher VO2 max than the unfit, meaning one group was significantly more fit than the other. It showed that one group participating in an exercise program (running 2-4 miles each day) gave the same RPE at a given HR as the unfit group not participating in an exercise program; despite moving at higher velocity. This indicates that RPE is a reliable measure of exercise intensity within a military population regardless of fitness level.

Role of Fatigue on Postural Control

Whole Body Fatigue

Activities that use the entire body; running, swimming, cycling, and walking, increase postural sway through hyperventilation and greater cardiac activity (Paillard, 2012). In addition, such activities have been shown to decrease sensory proprioception and exteroceptive information, and their subsequent integration, to help maintain posture. General body fatigue is also influenced by mental and psychological stress which has been shown to increase RPE during exercise (Vuillerme et al., 2001). Because general body fatigue is varied between individuals who have done the same amount of work or exercise, it can be difficult to reliably measure results among multiple subjects.

Fatigue, defined by Woods and Bigland-Ritchie as “the reduction in force generating capacity of the total neuromuscular system,” has been shown to affect stability. In a 2009 study, single-leg balance was shown to be negatively affected by fatigue in both men and women after both local and whole-body muscle fatigue. There was a significant increase in medio-lateral center or pressure (CoP) after both fatigue protocols. Men showed a greater increase in anterior-posterior CoP following the localized muscle fatigue protocol. Women showed a greater increase in anterior-posterior CoP following the whole-body fatigue protocol. Fatigue protocol used were localized-muscle fatigue; single-leg heel raises on a slant board until the movement could no longer be performed with the full range of motion. This protocol showed a reduction in concentric work of the calf by 26%. Whole-body fatigue was achieved using a rowing ergometer with the preferred leg strapped to a wheel platform to maintain a relaxed, extended position. The rowing exercise was done until volitional failure or established cadence could no longer be maintained. Springer and Pincivero choose this method due to the strong correlations between power output and heart rate with a rowing exercise. Results of the study showed no gender differences for localized-muscle fatigue. For both genders localized muscle fatigue showed greater effect on CoP distance in single-leg balance compared to whole-body fatigue and control groups. Localized muscle fatigue also caused greater anterior-posterior sway compared to medio-lateral sway. Anterior-posterior sway variability in the localized-fatigue condition for men and women was 29.6-39.2% (pre-to post) and 26.2-35.5% respectively. Compared to 28.0-29.7% and 25.5-32.9% for whole-body fatigue. Indicating that while fatigue, both whole-body and localized, affects balance; localized is more significant and anterior-posterior CoP distance is a more sensitive measurement of balance as it relates to fatigue (Springer & Pincivero, 2009). Overall the key finding in this study was that single-joint fatigue is just as detrimental to balance as whole-body fatigue. This suggests a central neurological process plays an important role in maintaining balance in both non-fatigue and fatigued states.

In 2008 a study done on subjects after both aerobic and anaerobic exercise showed that fatigue has a negative effect on postural sway. BESS test scores, performed on a force plate, decreased and greater postural sway velocity and sway area were all shown post-fatigue (Fox, Mihalik, Blackburn, Battaglini, & Guskiewicz, 2008). The effects were shown to last for 8-13 minutes once exercised ceased. Aerobic fatigue protocol consisted of 20m shuttle runs of increasing speed until the subject was considered fatigue; indicated by not reaching the end of 20m before a beep from a metronome. Anaerobic fatigue protocol consisted of 2 minutes of 20m sprints at maximal effort. HR and RPE were used to evaluate fatigue. Average RPE immediately after was 18.3 and 17.6 for aerobic and anaerobic respectively; average HR was 191 and 180 respectively (Fox et al., 2008). Both sway velocity and elliptical sway area increased equally from 4.89 to 8.15 and from 49.14 to 72.82 & 80.10 for aerobic and anaerobic protocols respectively three minutes after exercise. Eight minutes after exercise, aerobic sway velocity was 9.00, with anaerobic at 9.06. Elliptical sway area was at 62.46 and 61.82 for aerobic and anaerobic respectively after eight minutes.

Hyperventilation, both on its own and in association with physical activity, and increased heart-rate increase the amplitude of postural sway (Paillard, 2012). Data has shown that postural sway is affected after what is described as an exhaustive exercise test such as a VO2 max test or a two-mile run done at 93% of maximal heart-rate. The threshold indicated there is a significant effect on postural sway shown to be the 60% of maximal heart-rate of the subject. Postural sway is not influenced by activities that require less than 60% of maximal heart-rate, provided the activity duration is less than one hour. Longer activities with a lower intensity have also been shown to effect postural sway.

According to Paillard et al., 2012, the effects of general fatigue on postural stability are caused primarily by; dehydration, disturbances of sensory information, and metabolic products produced as a result of exercise. Dehydration has been shown to cause a significant difference in subjects who perform exercise on an ergo cycle. Subject who drank during exercise had decreased postural disturbances compared to those who did not drink. Dehydration causes a loss of fluid, mainly endolymphatic, which alters vestibular function (Sakuma et al., 1996). Metabolite products have been shown to disturb postural control by reducing the efficiency of the stretch reflex and reduced motor output accuracy in muscles involved in posture (Windhorst, 2007).

Visual input can compensate for decreased contribution of postural control due to loss of proprioception (Derave et al., 2002). However, the ability to compensate can decrease due to the visual-dynamic nature of the exercise. There is a contrast between a stationary bike test for fatigue and a running test in that the field of vision during running is constantly changing. After running there is a conflict between somatosensory and motor information that remains from the exercise despite the movement itself no longer being performed (Lepers et al., 1997). The effect resolves once the visual input and motor drive have restored. Because of the visual disturbance a running fatigue protocol will cause a greater postural disturbance than a stationary bike test or other activity that involves little or no head movement.

There are proprioceptive differences in effects of posture between general fatigue activities such as cycling, running, and walking. EMG data shows increased activation in the leg muscle more in walking and running than cycling where there is a relatively higher activation of thigh muscle. This is due to the muscles involved in walking and running also being involved more in postural control. This is another way in which, when intensity is controlled for, a walking or running exercise will cause a greater change in postural control post-exercise. In summary, the main factors to consider when evaluating the effect of fatigue on general whole-body fatigue are: physiological disturbances, central fatigue (dependent on duration and intensity), mechanical constraints (decreased maximal voluntary contraction of muscles), sensory disturbance, dehydration, and method of fatigue (seated cycling versus walking or running).

Local Fatigue

Research done on local muscle fatigue typically uses repeated simple movement meant to fatigue the muscles being investigated. Fatigue is then measured based on contraction force, volitional fatigue, or there is a predetermined amount of work (repetitions or total weight moved) that each subject performs. Data collected from multiple studies by Paillard, 2012 shows that the mean CoP velocity increases significantly when MVC decreases by 30%. No effect is seen if MVC is less. However, like general fatigue at a lower intensity over a long period; there is a decrease in postural control at an MVC loss of 6% in an exercise lasting at least 30 minutes. It is likely that this is related to central fatigue and a decreased control of movement.

As the number of muscles activated increases in an exercise, the greater the increase in postural disturbance (Paillard, 2012). Subjects showed less postural disturbance with heel raise exercises compared to squat exercise. In the case of both types of exercise it is worth noting that until the threshold for fatigue, discussed above is reached, the body will successfully compensate for the fatigued muscles. Muscle properties change when submaximal contractions are maintained until exhaustion. This causes a decrease in motor output as conduction velocity of afferent nerves decreases with fatigue. In general, local fatigue effects motor output more than sensory input, such as that which occurs in walking or running, in the case of postural disturbance. EMG data has indicated that neuromuscular control and posture is restored before the muscle is recovered. This is likely due to the body prioritizing functional task such as balance over motor performance.

Recovery of posture is dependent more on the length of the fatigue exercise more than the intensity. Yaggie and Mcgregor (2002) observed that a MVC loss of 50% increased the length of CoP displacement for 20 min after fatiguing exercise. However, Dickin and Doan (2008) noted that the disturbance was maintained for 30 min after MVC loss of 30%" (Paillard, 2012). The joint that is fatigued influences the recovery time. Postural control is restored faster after a knee exercise compared to an ankle exercise (Paillard, 2012).

The importance of inducing enough fatigue to influence balance can be seen in studies that fail to show a difference in individuals who show no difference in postural control before and after fatigue a protocol. In 2009, Bellow et al. attempted to compare fatigue of hip abductors on balance control in younger and older women. Results showed that fatigue in the hip abductors did not cause a decrease in balance control. The protocol used hip abduction motion through 50% of available active ROM, with 3% of the subject's body weight applied to the ankle. Fatigue was considered to be achieved when the subject failed to hit the target ROM or became out of synch with the pacing for three consecutive repetitions (Bellew, 2009). The authors state that some subjects showed a clear maximal effort but others, more often in the older group, terminated their effort once they felt they had worked hard enough.

With no measure of loss of MVC it is impossible to tell how much fatigue occurred in the hip abductors after the protocol. The majority of subjects, more so in the older group, reported feeling little to no effect from the fatigue protocol by the end of the balance tests. This demonstrates the need to quantify local muscle fatigue to ensure a desired degree of fatigue is reached in subjects. As shown by Yaggie and Mcgregor, (2002) there is a threshold for local fatigue to cause disruption in balance. Using MVC will still leave room for other limitations in data collection but it helps to ensure that any change in balance is due to compensation or recovery.

Fatigue in specific joints has been observed to influence single leg stability. Each joint has a unique effect on CoP movement in a balance task. To investigate fatigue in the hip researchers used a Biodex system III and subjects were measured for MVCs at 30 degrees for the extension and 120 degrees for the flexion. The fatigue protocol consisted of maximal isokinetic flexion and extension for as many repetitions as possible. Subjects were considered fatigued when three consecutive repetitions were below 50% of the MVC torque for both flexion and extension muscle groups (Bisson, McEwen, Lajoie, & Bilodeau, 2011.) Data indicated that fatigue in the hip and knee had a greater effect on postural control than fatigue in the more distal ankle muscles. Fatigue in the hip showed increased sway variability and velocity in both anterior-posterior and medio-lateral directions in a unipedal stance. This is despite a fatigue protocol that only involved anterior-posterior muscles in flexion and extension movements. It is noted in this paper, and other that while hip fatigue increased sway velocity by 13% in the medio-lateral directions; ankle fatigue only increased sway velocity by 2% in the same direction. Maintaining stability from the hip increases with the difficulty of the task. For example, when proprioception at the ankle is reduced, like standing on a foam surface, there is a greater reliance on the hip for stability.

During bipedal stance, the body is able to use contralateral compensation to maintain balance. Unipedal stance is more difficult to compensate for, but data indicates that when a distal muscle or joint is fatigued a more proximal muscle will compensate (Bisson et al. 2011). For example, an ankle fatigue protocol followed by a unipedal stance task showed increased activation in hip muscle compared to pre-fatigue data. A study investigating fatigue used a Stairmaster to fatigue subjects to less than 50% of an initial tested strength, using a dynamometer (Johnston et al., 1997). Pre-and post-fatigue tests were done using a bipedal and unipedal stance on a KAT platform to determine postural control. Authors note that "all our subjects were able to stand easily after the fatigue portion of the test, and the act of balancing on the platform of the devices is, in and of itself, not physically demanding." They also show that while balance is maintained there was a decrease in balance assessment. This is a good example of the body compensating for fatigue using different, less fatigued muscles, to maintain balance. It is worth noting that an increase in attentional demand, in a dual-task, was not observed. This lead authors Bisson et al. to conclude that there are sufficient attentional resources to perform a dual task after a physical fatigue protocol in hip and ankle joints.

Proprioception of the ankle has been shown to be a primary regulatory mechanism for the body in stabilization (Di, Maganaris, Baltzopoulos, & Loram, 2009). Subjects who were asked to perform plantar and dorsiflexion movements of the ankle before and after fatigue protocols. Subjects were in a seated position at a desk in such a way that they could not see their ankle but could know the position of their ankle based on an oscilloscope in front of them. The study showed how an isometric exhaustion test affects the proprioception at the ankle using an active matching task (Forestier, Teasdale, & Nougier, 2002). Target angle positions of the ankle were 20 and 10 degrees of plantar and dorsiflexion. For accurately of ankle position, left ankle reference and target positions were displayed on the oscilloscope. In each trial, a target position was given verbally to each subject. The tasks were performed a total of 100 times in both fatigue and non-fatigue conditions. The right leg was chosen for inducing fatigue due to its general preference for precision and control in daily tasks. A dynamometer was used to measure MVC of the tibialis anterior. For the fatigue protocol subjects were instructed to maintain a workload of 70% of MVC for 40 seconds with a 40 second rest interval. The tibialis anterior was considered fatigued when the subject was unable to maintain workload for more than 15 seconds. Data collection began immediately post fatigue protocol.

Data showed that constant error and variable error were not affected for a neutral ankle position, showing that subjects were able to position their ankle accurately after fatigue. Three-way ANOVA interaction, for absolute error (absolute deviation from position of the right ankle and the point of reference), of fatigue × Direction × amplitude showed an effect of fatigue on 20 degrees of dorsiflexion and 10 degrees of plantarflexion. Therefore, subjects in a fatigued condition produced greater absolute errors for large amplitude movements of dorsiflexion and small amplitude movements of plantar flexion. This study showed that there are limits to the ability of the central nervous system to compensate for physical fatigue at the ankle. This can result in a sensation of feeling clumsy and unstable after a period of intense physical exercise (Forestier et al., 2002).

This concurs with data by Springer & Pincivero that showed medio-lateral sway for whole-body fatigue pre-and post-test to be 21.2-22.0% and 24.0-20.9% for men and women respectively. With localized-muscle fatigue showing relatively lower effects on medio-lateral sway, 20.1-24.4% and 22.7-28.6% for men and women respectively. Impairment in both quiet stance and gait have been identified one month after concussion diagnosis. Meaning the risk of injury from impaired stability remains for at least as long.

A key difference in balance when investigating different types of fatigue is compensation. When using a local fatigue exercise there is a smaller proportion of postural muscles used. The central nervous system can compensate for the fatigue of one, or a one group, of muscles by activating others. This partially explains why some studies that have used local fatigue have shown little to no effect on posture post-fatigue (Paillard, 2012). From the point of applying such data, the whole-body fatigue task would more closely match what is seen outside a lab. Falls that result from loss of postural control usually occur after a longer or more intense period of activity that involves the whole body. Activities in sports or military training more often involve tasks that are more like walking or running tasks than ankle plantar and dorsiflexion tasks alone.

Current Gaps in the Literature

As shown above, fatigue and its effects on postural control have been investigated. What is unknown is the role fatigue has on objective tests of postural control that are increasingly used in civilian and military athletic communities. Fox et al. (2008) Benedict et al. (2017) examined this question, but each study only used one objective balance assessment and one measure of perceived fatigue (RPE). The goal of this thesis was to use objective measures of postural control. (BTracks, and AccWalker) to examine the effects of perceived fatigue (measured by RPE and the NASA-TLX) after a standardized fatiguing protocol. This will help close the gaps in the literature by providing a stronger understanding of how fatigue may influence the clinical interpretation of objective postural control assessments.

CHAPTER III

OUTLINE OF PROCEDURES

Participants

Subjects were recruited from University of North Carolina at Greensboro (UNCG) and the local community. To control for subject's fitness, each subject must have been currently engaged in a minimum of three hours of vigorous activity each week. This was confirmed via email or verbally before participation in the study.

Instrumentation

The two objective measurements of balance used were BTrackS portable force plate (Chang, Levy, Seay, & Goble, 2014) and the AccWalker smartphone app (Kuznetsov et al., 2018; Rhea et al., 2017). The BTrackS Balance Test consisted of three trials, each done standing still on a portable force plate with the eyes closed (Figure 1). The AccWalker test consisted of stepping-in-place for 70 seconds with the eyes closed and while shaking the head from side-to-side with a smartphone attached to the thigh (Figure 2). A metronome provided the target stepping pace for the first 10 seconds and the participant then attempted to keep that pace for the next 60 seconds. Two trials of each condition were collected for reliability purposes (Kuznetsov et al., 2018).

The fatiguing test was the similar to that used by Benedict et al. (2017); consisting of:

1) 3 minutes of 20-metersprints

2) 2 minutes of pushups

3) 2 minutes of sit ups

4) 3 minutes of step ups

5) 3 minutes of sprints

Before and after the fatigue protocol, two measurements of fatigue were taken: the Borg 6-20 RPE scale (Borg, 1982) and the NASA-TLX (Hart, 2006) (Figure 3)

Figure 1. The BTrackS Balance Assessment on a Portable Force Plate. Image from Benedict et al. (2017).

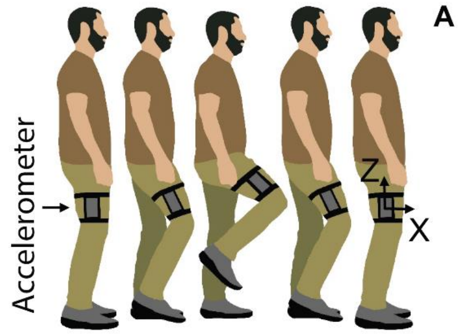
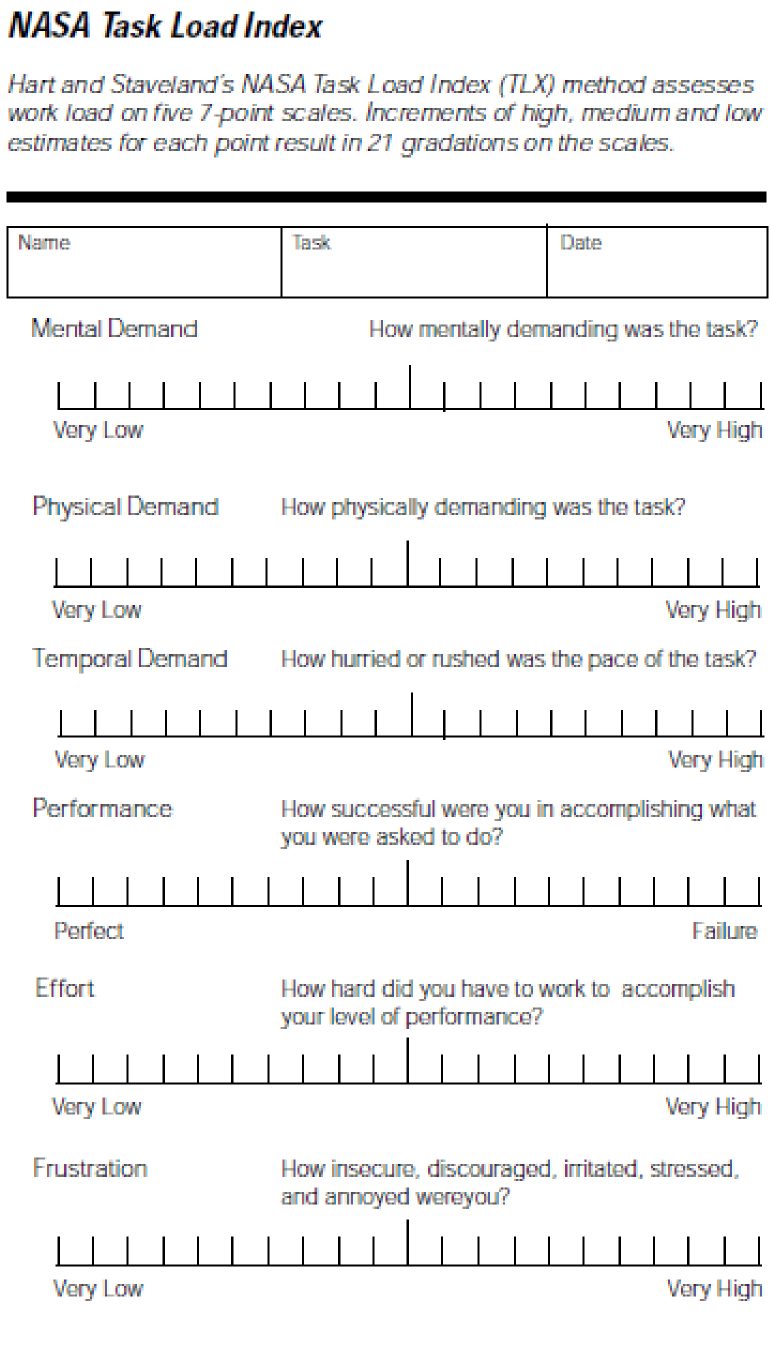


Figure 2. The AccWalker Balance Assessment Using a Smartphone App. Image from Rhea et al. (2017).



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure 3. The NASA-TLX (Hart, 2006)

Procedure

After completing the informed consent, participants followed the procedure outlined in Figure 4. The order of the postural control assessments was counterbalanced between each test session to control for a potential order effect.

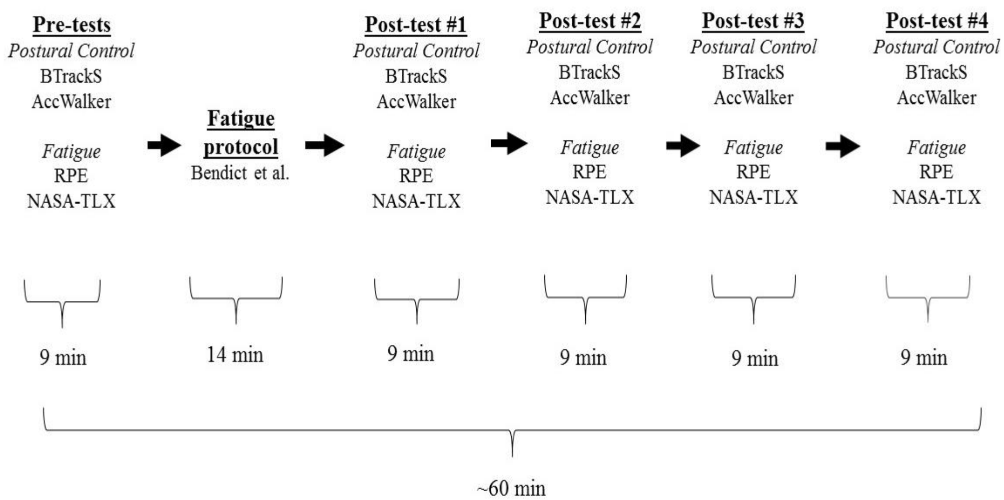


Figure 4. Flow and Timing of Testing for This Project.

Dependent Variables

The dependent variables (DVs) were the following:

BTrackS: Total excursion of the CoP (cm)

AccWalker: SD of stride time (sec)

AccWalker: SD of peak thigh flexion (deg)

RPE: score from 6-20

NASA-TLX: Overall workload score on each of the five 7-point scales

Statistical Approach

Prior to addressing hypothesis 1, the RPE and NASA-TLX scores across the five time points (pre-test, 0-9 min post-test, 9-18 min post-test, 18-27 min post-test, and 27-36 min post-test) were included in a multivariate analysis of variance (MANOVA) to determine whether the scores changed after the fatiguing protocol. If significant, follow-up univariate ANOVAs were used to determine which perceived fatigue variable(s) changed and pairwise comparisons were then used to determine which time points differed from each other.

Hypothesis 1: A decline in postural control will be observed immediately after the fatigue protocol, but will return to baseline levels after 9 minutes

To address hypothesis 1, a series of MANOVAs were used. For AccWalker the first MANOVA included stride time SD in the eyes closed and head shake conditions and the second MANOVA included peak flexion SD in the eyes closed and head shake conditions. The same follow-up procedure described for the perceived fatigue variables was used for the AccWalker data if warranted. For the BTrackS Balance Test data, a repeated measures ANOVA was used to examine changes across the five time points, with follow-up pairwise comparisons used if appropriate. If the data exhibited a non-normal distribution (confirmed by Mauchly's test of sphericity), then the Greenhouse-Geisser correction was used.

Hypothesis 2: The magnitude of the immediate postural control decline will be associated with an individual's level of perceived fatigue.

To address hypothesis 2, the magnitude of change in postural control performance and perceived fatigue was first measured by quantifying the difference between the pre-test and 0-9 min post-test scores for each DV. Next, the association between the postural control difference score and fatigue difference scores was be examined by running separate correlation analyses using Spearman's rho due to the nonparametric nature of the data.

CHAPTER IV

MANUSCRIPT

Introduction

Postural control is defined as the ability to maintain upright stance, which is accomplished through a complex and dynamic process that integrates both internal and external factors (Winter, Patla, & Frank, 2010; Oie et al., 2002). Humans are, to some degree, inherently unstable, which affords the flexibility to respond to unexpected perturbations that occur in daily life. Thus, a certain level of instability contributes to our ability to functionally interact with the environment and complete tasks associated with activities of daily living or those more specialized in nature. In a healthy system, the postural control response is ideally proportionate to the disturbance to maintain upright stance (Rietdyk, Patla, Winter, Ishac, & Little, 1999, Adkin, Frank, Carpenter, & Peysar, 2000). When postural control is compromised, it will exhibit delayed timing and/or reduced magnitude in response to a disturbance (Claudino, dos Santos, & Santos, 2013, Gago, Yelshyna, Bicho, Silva, Rocha, Rodrigues, & Sousa, 2016). It is well documented that postural control instability increases when the neurosensory systems contributing to postural control (vision, vestibular, and proprioceptive) are compromised (Peterka, 2002). What is less understood is the role fatigue has on postural control. Since postural control tasks are commonly used to assess neuromotor behavior in athletic populations (Chang et al., 2014), examining how fatigue influences performance on postural control tests would help clinicians better determine whether a decline in performance is due to fatigue or a compromised neurosensory system.

Fatigue is a complex process that can be considered at the local or whole-body levels. Local fatigue occurs when one muscle, or muscle group, is unable to produce a force needed to accomplish a task. This approach, while commonly used in a laboratory setting, is less ecological valid relative to real-world applications. Alternatively, whole body fatigue involves multiple muscle groups. However, there is currently no way to validly or reliability measure whole body fatigue. As a result, researchers typically rely on self-reported measures of perceived exhaustion or perceived workload as a surrogate to fatigue. The Rating of Perceived Exhaustion (RPE) has a long history of being used in this context (Chen, Fan, & Moe, 2002). RPE has also been shown to be a valid indictor of physiological work, as Chen et al. (2002) showed that RPE was related to heart-rate and total work done, with variation between genders and active versus inactive subjects. For the purposes of this study, fatigue will be referred to as “perceived fatigue” in an effort to convey it is the subjects feeling of fatigue and not a measurable variable, such as heart rate. Relative to perceived workload, the NASA Task Load Index (NASA-TLX) is a multidimensional assessment of the perceived workload associated with a task (Hart, 2006). The NASA-TLX gives an amalgamation of physical, mental, and emotional factors required to complete a task. The cognitive component of the NASA-TLX will help reveal how mentally challenging each postural control task is relative to the time since completing the fatigue protocol. This, in addition to the more physically based exertion measure of RPE, will give a more complete measure of perceived fatigue in the individual. This tool also has been previously used to assess perceived workload in motor behavior tasks (Raisbeck, Diekfuss, Wyatt, & Shea, 2015; Diekfuss, Ward, & Raisbeck, 2017; Raisbeck & Diekfuss 2015; Raisbeck & Diekfuss, 2017). Using both RPE and the NASA-TLX as surrogates of perceived fatigue would help more fully characterize the influence of fatigue on postural control.

Postural control performance is commonly assessed using a static balance test, in which the goal is to maintain the center of mass (COM) within the base of support (BOS). Clinically, these tests are typically administered as an upright stance task and the tester subjectively assesses the participant's ability to remain relatively still. In athletic populations, the Balance Error Scoring System (BESS) is one of the most commonly used balance tests (Guskiewicz, 2011; Bell, Guskiewicz, Clark, & Padua, 2011). However, questions about the validity and reliability of the BESS have been raised (Buckley, Oldham, Caccese, 2016; Finnoff, Peterson, Hollman, & Smith, 2009; Reed-Jones, Murray, Powell, 2014; Rochefort, Walters-Stewart, Aglipay, Barrowman, Zemek, Sveistrup, 2017), which focus on the challenges associated with the subjective nature of the test. To overcome this challenge, a portable forceplate (termed the BTrackS Balance Test) has been developed that provides researchers and clinicians the ability to objectively measure postural control by quantifying the amount of movement of the center of pressure (COP) while the participant stands still on the device (Goble, Manyak, Abdenour, Rauh, & Baweja, 2016; Benedict, Hinshaw, Byron-fields, Baweja, & Goble, 2017). After an injury to the neurosensory system, such as a concussion, there is an increase in COP movement seen on the BtrackS. In comparison to healthy subjects, those with compromised postural control will sway more. Thus, adopting the portable forceplate meets the challenge of using objective measurement, but it still relies on a static stance task. Dynamic postural control is required in many real-world tasks and adopting a dynamic postural control task can lead to stronger sensitivity and specificity when attempting to identify neuromotor dysfunction. To address the need of an objective and dynamic balance test, Rhea and colleagues developed a smartphone app that measures postural control while the participant performs a stepping-in-place task. This test (termed AccWalker) has been shown to be a reliable and valid way to measure postural control (Kuznetsov et al., 2018), as well as a clinically useful tool to identify neuromotor dysfunction after head trauma (Rhea et al., 2017). After a perturbation to the neurosensory system there is an increase in standard deviation of both peak thigh flexion and stride time in the AccWalker test. It is unknown how perceived fatigue affects this dynamic balance test.

The effect of perceived fatigue on the postural control has previously been examined (Fox et al., 2008, Benedict et al., 2017) and showed the time course that could be expected for fatigue to return to baseline levels after a fatiguing protocol. However, there were limitations to this previous work. First, both studies used RPE to assess postural control deficits after a fatiguing protocol, but neither study examined the extent to which an increase in RPE related to an increase in postural instability. Second, neither study included a measure of perceived workload, which would add a different dimension of perceived fatigue to the assessment. Third, both studies only used a static postural control task while on a forceplate. Therefore, the purpose of this study was to examine the effects of perceived fatigue (measured by RPE and the NASA-TLX) on objective postural control tests (measured by the BtrackS Balance Test and AccWalker). It was hypothesized that (1) a decline in postural control will be observed immediately after the fatigue protocol, but will return to baseline levels after 9 minutes and (2) the magnitude of the immediate postural control decline will be associated with an individual's level of perceived fatigue.

Methods

Participants (N=30, 33.6±14.2 years) were recruited from the local community. Inclusion criteria included a self-report of current participation in at least three hours of vigorous physical activity per week and no current musculoskeletal injuries. Prior to data collection, participants read and signed a consent form. The study protocol and consent form were approved by the Institutional Review Board at the University of North Carolina at Greensboro.

All participants wore athletic clothes/shoes and completed the same testing protocol: (1) one pre-test assessment of perceived fatigue and postural control, (2) a fatiguing protocol that took approximately 14 minutes to complete, and (3) four post-test assessments of perceived fatigue and postural control spaced out over four windows that were nine minutes in duration each, which was the shortest window duration possible to complete all of the perceived fatigue and postural control assessments. The postural control assessment in the pre- and post-tests included the BTracks Balance Test, sampling frequency of 25Hz, and AccWalker, sampling frequency of 100Hz. The BtrackS Balance Test consisted of three 20-second standing trials on a portable forceplate with eyes closed. The AccWalker protocol required participants to step in place to the sound of a metronome for the first 10 seconds, followed by 60 seconds of stepping in place while attempting to maintain the same pace after the metronome turned off. Congruent with the protocol described in Kuznetsov et al. (2018), this task was completed with the eyes closed (to perturb the visual system) and while laterally shaking the head (to perturb the vestibular system), with each condition performed twice and the performance averaged between the two trials within each condition. One practice trial of the eyes closed and head shake conditions were provided prior to the pre-test for familiarization purposes. The BtrackS Balance Test and AccWalker order was counterbalanced in order to control for an order effect. After each postural control test, the participants were asked “what is your current RPE?” and they indicated their answer verbally or by pointed to the RPE chart held in front of them. Then the subject completed the NASA-TLX form on their own, which was quantified by adding the scores from all the questions. The same procedure and order of operations was used during each of the four post-test sessions. The post-test sessions were completed within a window of nine minutes and repeated four times, providing a measurement of postural control four times over a 36-minute post-fatigue window.

After the pre-test session, a fatigue protocol was implemented that was similar to Benedict et al. (2017). Participants were given five minutes of self-selected warm-up before beginning the protocol. The fatigue protocol started with three minutes of 20 m sprints. A lane was marked with black tape on the side and lines to mark the end of the 20 m; participants touched the end of each 20 m with their hand. After sprints were performed, subjects immediately moved to two minutes of pushups followed by two minutes of sit-ups, three minutes of step ups and three more minutes of 20 m sprints. After the second set of sprints the subject would, as quickly as possible, begin the first postural post-test session. Estimated average time between ending the fatigue protocol and beginning the first post-test session was less than one minute.

The dependent variables for perceived fatigue were RPE and NASA-TLX scores. The dependent variable for the BTrackS Balance Test was the average total excursion of the COP over the three trials. The dependent variables for AccWalker were standard deviation (SD) of stride time (measured in seconds) and peak thigh flexion (measured in degrees). Prior to addressing hypothesis 1, the RPE and NASA-TLX scores across the five time points (pre-test, 0-9 min post-test, 9-18 min post-test, 18-27 min post-test, and 27-36 min post-test) were included in a multivariate analysis of variance (MANOVA) to determine whether the scores changed after the fatiguing protocol. If significant, follow-up univariate ANOVAs were used to determine which perceived fatigue variable(s) changed and pairwise comparisons were then used to determine which time points differed from each other. To address hypothesis 1, a series of MANOVAs were used. For AccWalker the first MANOVA included stride time SD in the eyes closed and head shake conditions and the second MANOVA included peak flexion SD in the eyes closed and head shake conditions. The same follow-up procedure described for the perceived fatigue variables was used for the AccWalker data if warranted. For the BTrackS Balance Test data, a repeated measures ANOVA was used to examine changes across the five time points, with follow-up pairwise comparisons used if appropriate. If the data exhibited a non-normal distribution (confirmed by Mauchly's test of sphericity), then the Greenhouse-Geisser correction was used. To address hypothesis 2, the magnitude of change in postural control performance and perceived fatigue was first measured by quantifying the difference between the pre-test and 0-9 min post-test scores for each DV. Next, the association between the postural control difference score and fatigue difference scores was be examined by running separate Pearson correlations.

<u>Results</u>

For perceived fatigue, the MANOVA indicated there was a change across time points, $F(8,17) = 11.70$, $p < .001$, Wilk's $\Lambda = 0.154$, partial $\eta^2 = .846$. The follow-up univariate ANOVAs showed both RPE, $F(2.05, 49.31) = 36.28$, $p < .001$, partial $\eta^2 = .602$, and NASA-TLX, $F(1.98, 47.46) = 14.16$, $p < .001$, partial $\eta^2 = .371$ changed across the time points. For RPE, the pairwise comparisons showed a significant increase between the pre-test (8.1±1.6) and the 0-9 min post-test (13.0±2.8). RPE remained elevated at the 9-18 min and 18-27 min post-tests (10.4±2.3 and 9.2±1.9, respectively), returning back to baseline at the 27-36 min post-test (8.8±2.1) (Figure 5). For the NASA-TLX, the pairwise comparisons showed a significant increase between the pre-test (5.3±2.4) and the 0-9 min post-test (7.7±3.7), then returning back to baseline levels at the 9-18 min, 18-27 min, and 27-36 min post-tests (5.6±3.1, 4.7±2.4, and 4.4±2.2, respectively) (Figure 6).

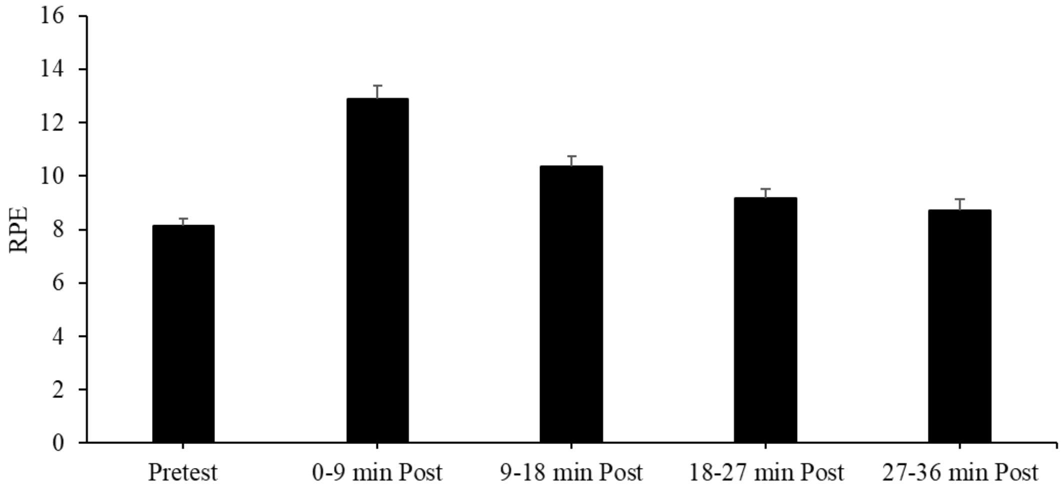


Figure 5. Rating of Perceived Exertion (RPE) data. RPE before (Pretest) and in each of the four windows of time after the fatiguing protocol (0-9, 9-18, 18-27, and 27-36 min Post). The asterisk indicates a significant difference from the Pretest.

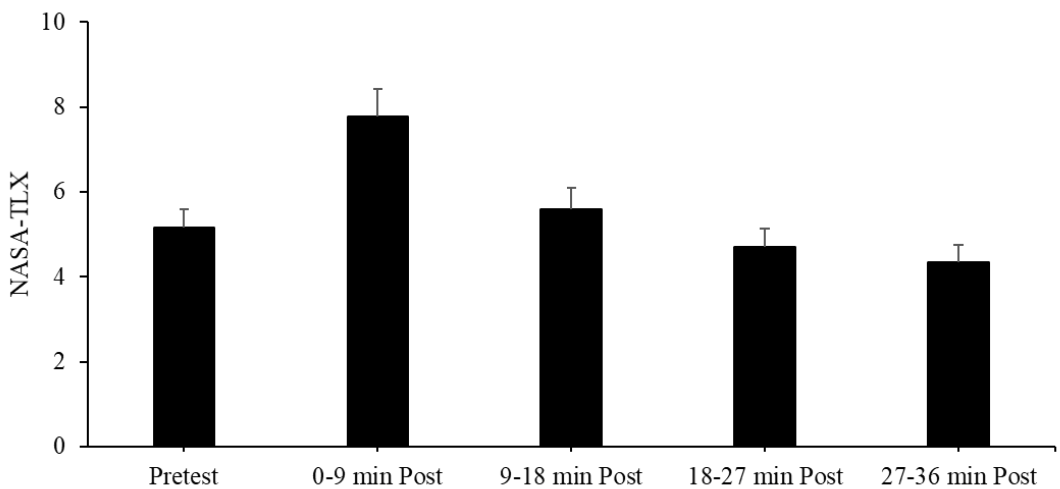


Figure 6. NASA Task Load Index (NASA-TLX) data. NASA-TLX before (Pretest) and in each of the four windows of time after the fatiguing protocol (0-9, 9-18, 18-27, and 27-36 min Post). The asterisk indicates a significant difference from the Pretest.

The MANOVA for AccWalker stride time SD indicated there was no change across time points in the eyes closed or head shake conditions, $F(8,11) = 1.13$, $p = .416$, Wilk's Λ = 0.549, partial $\eta^2 = .451$. Since the MANOVA was not significant, no follow-up statistics were run. Stride time standard deviation in both conditions at each time point are presented in Figure 7 (eyes closed) and Figure 8 (head shake).

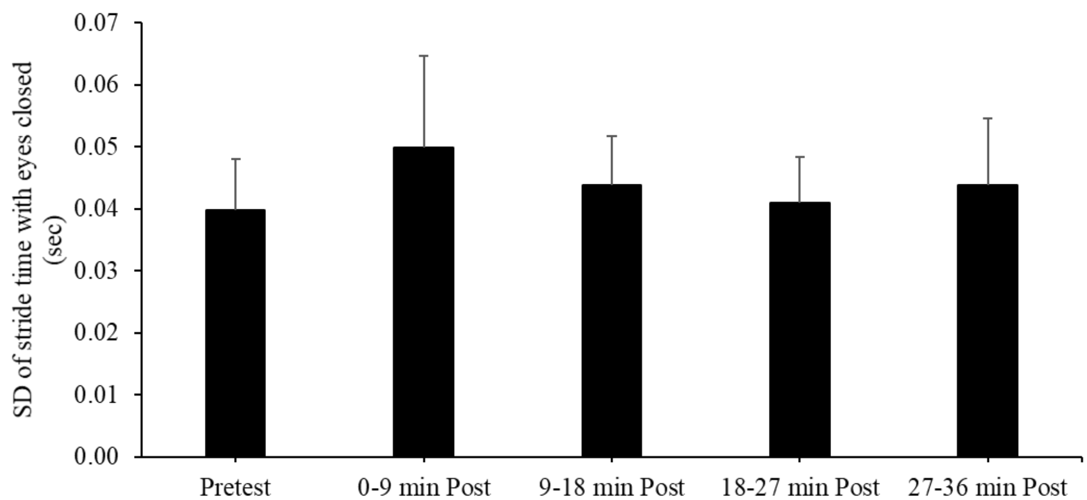


Figure 7. Standard Deviation (SD) data of Stride Time With Eyes Closed During the AccWalker Dynamic Balance Test. Data are presented before (Pretest) and in each of the four windows of time after the fatiguing protocol (0-9, 9-18, 18-27, and 27-36 min Post).

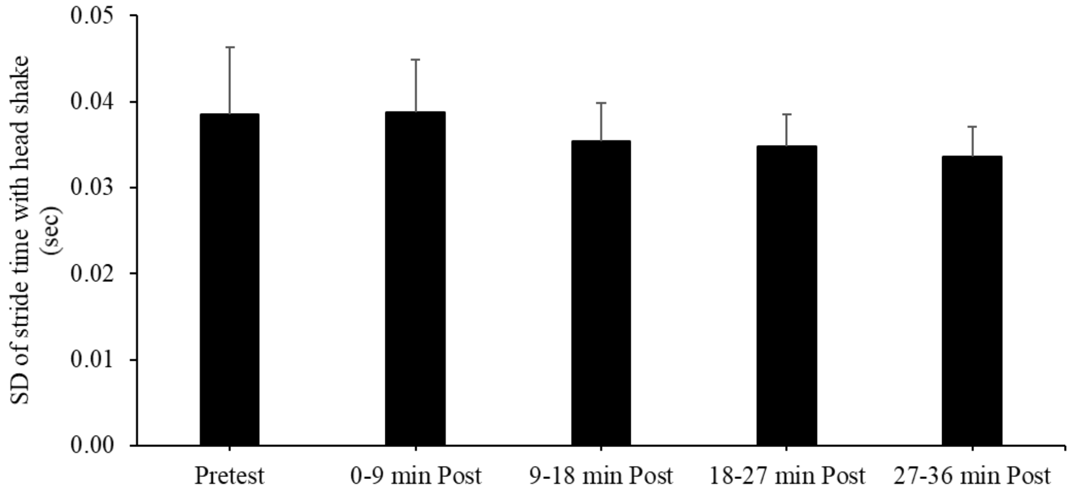


Figure 8. Standard Deviation (SD) data of Stride Time With Head Shake During the AccWalker Dynamic Balance Test. Data are presented before (Pretest) and in each of the four windows of time after the fatiguing protocol (0-9, 9-18, 18-27, and 27-36 min Post).

The MANOVA for thigh flexion SD indicated there was not a change across time points in the eyes closed or head shake conditions, $F(8, 13) = 2.15$, $p = .106$, Wilk's $\Lambda = 0.431$, partial $\eta^2 = .569$. Since the MANOVA was not significant, no follow-up statistics were run. Thigh flexion standard deviation in both conditions at each time point are presented in Figure 9 (eyes closed) and Figure 10 (head shake).

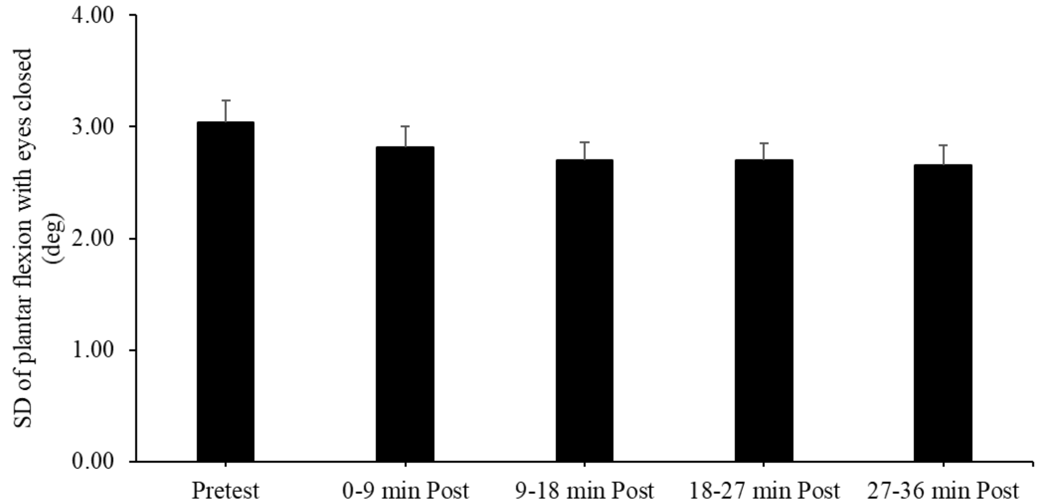


Figure 9. Standard deviation (SD) data of Plantar Flexion With Eyes Closed During the AccWalker Dynamic Balance Test. Data are presented before (Pretest) and in each of the four windows of time after the fatiguing protocol (0-9, 9-18, 18-27, and 27-36 min Post).

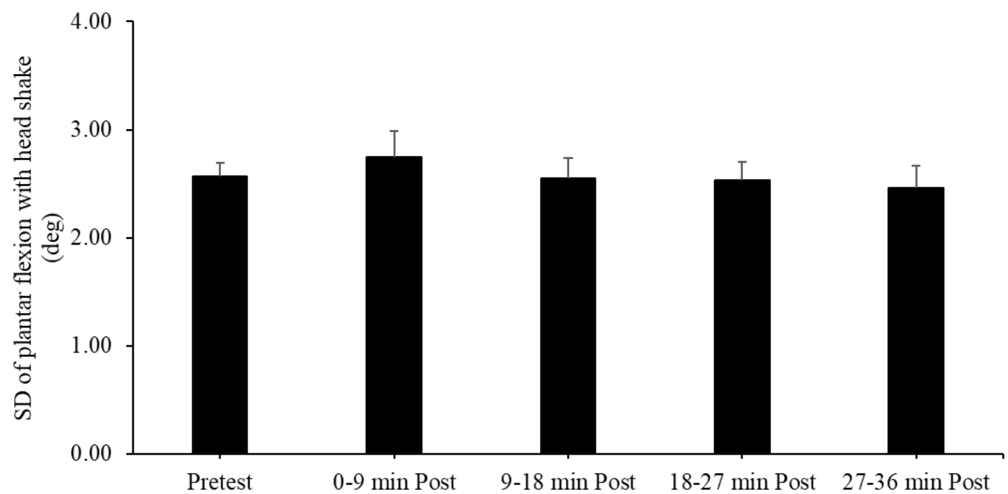


Figure 10. Standard Deviation (SD) data of Plantar Flexion With Head Shake During the AccWalker Dynamic Balance Test. Data are presented before (Pretest) and in each of the four windows of time after the fatiguing protocol (0-9, 9-18, 18-27, and 27-36 min Post).

For the BtrackS Balance Test, the repeated measures ANOVA indicated there was a change across time points, $F(2.36,58.95) = 6.07$, p = .003, partial $\eta^2 = .195$. Follow-up the pairwise comparisons showed a significant increase between the pre-test (19.5±5.4 cm) and the 0-9 min post-test (25.1±7.8 cm), then returning back to baseline levels at the 9-18 min (21.7±7.5 cm), 18-27 min (20.5±7.7 cm), and 27-36 min (20.3±6.5 cm) (Figure 11).

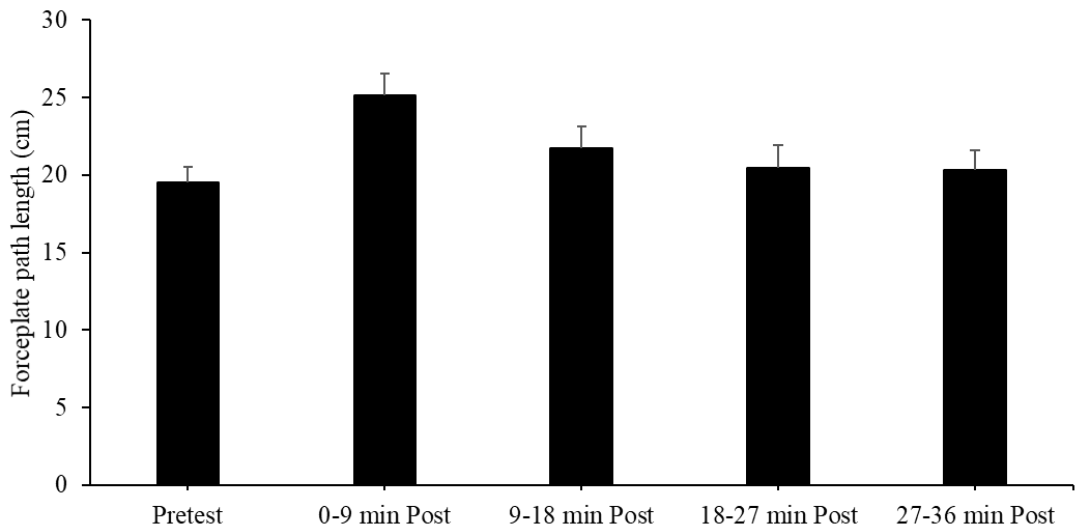


Figure 11. Path Length data of the Center of Pressure (CoP) While Standing on the Forceplate During the BTrackS Balance Test. Data are presented before (Pretest) and in each of the four windows of time after the fatiguing protocol (0-9, 9-18, 18-27, and 27-36 min Post). The asterisk indicates a significant difference from the Pretest.

For hypothesis two, all correlations are presented in Table 1. The only significant association between the change in perceived fatigue and the change in postural control was between the NASA-TLX and AccWalker thigh flexion SD in the head shake condition, $r_s(25)=.492$, $p = .012$. A significant correlation was observed between the two perceived fatigue assessments, $r_s(30)=.544$, $p = .002$ and between AccWalker stride time

SD in the eyes closed and head shake conditions, $r_s(21)=.435$, $p = .049$. A near signification correlation was observed between AccWalker stride time SD in the eyes closed condition and the BTrackS Balance Test, $r_s(25)=.350$, $p = .086$.

Table 1. Spearmans Rho Correlations Between Change in Fatigue and Postural Control From the Pre-test and 0-9 min Post-test

Measure	1	2	3	4	5	6	7
1. Change in RPE							
2. Change in NASA-TLX	0.544**						
3. Change in AccWalker stride time SD with EC	0.198	0.074					
4. Change in AccWalker stride time SD with HS	-0.018	-0.062	0.435*				
5. Change in AccWalker plantar flexion SD with EC	-0.044	-0.079	0.155	-0.165			
6. Change in AccWalker plantar flexion SD with HS	0.241	0.492*	0.102	0.164	-0.309		
7. Change in BTrackS Balance Test	-0.201	-0.188	0.060	0.350	-0.051	-0.071	

* indicates $p < .05$, ** indicates $p < .01$

<u>Discussion</u>

The purpose of this study was to examine the effects of perceived fatigue (measured by RPE and the NASA-TLX) on objective postural control tests (measured by the BtrackS Balance Test and AccWalker). Two hypotheses were tested. Hypothesis one stated that a decline in postural control would be observed immediately after the fatigue protocol, but will return to baseline levels after 9 minutes. Data from the BtrackS Balance Test supported this hypothesis, but AccWalker data showed no changes after the fatigue test. Hypothesis two stated the magnitude of the immediate postural control decline would be associated with an individual's level of perceived fatigue. Data from only one pair of variables (NASA-TLX and AccWalker thigh flexion SD) provided support for this hypothesis. Collectively, the data showed that the BtrackS Balance Test is acutely affected by perceived fatigue, but AccWalker showed no changes in performance after the fatigue protocol.

The first step in this study was to show that the fatigue protocol led to an increase in perceived fatigue, which was observed in both RPE and the NASA-TLX. Specifically, RPE was elevated up to 27 minutes after the fatigue protocol, but the NASA-TLX was only elevated up to 9 minutes after the fatigue protocol. While similar perceived fatigue was observed acutely—evidenced by the positive correlation in the change in RPE and NASA-TLX tested in hypothesis two—the manner in which perceived physical fatigue (indexed by RPE) and perceived workload (indexed by NASA-TLX) recover appear to be at different rates after the fatigue protocol. Some recent studies using subjective/perceived fatigue measures have used both RPE and NASA-TLX such as Baghdadi et al (2017) and Vera et al (2018) to measure how fatigue affects manufacturing tasks and cycling tasks respectively. To our knowledge, this is the first study comparing the relation between perceived physical fatigue and perceived workload after a physically demanding protocol and our data suggest they degrade at different rates after physical exertion. The relatively fast rate of recovery in the NASA-TLX measure may indicate that cognitive workload may be less affected by a more physically fatiguing task. In addition, the NASA-TLX asks more questions; therefore, it may elicit a more detailed response from the subject. Giving more of a profile of the manner of fatigue instead of a single numeric measuer.

The BTrackS Balance Test and AccWalker test are both objective measurements of postural control. The BTrackS Balance test uses a forceplate, which measures the displacement of the CoP over 20 second trials. There was a significant increase in the total excursion of the CoP between the pre-test and first post-test, indicating that perceived fatigue caused a decrease in postural control as assessed by the BTrackS Balance Test. As predicted, postural control retuned to the pre-test level after the first post-test window, suggesting that effect of fatigue the BTrackS Balance Test lasts less than nine minutes. This observation supports previous findings by Benedict et al. (2017), who showed that the BTrackS Balance Test performance returned to pre-fatigue levels within five minutes after the same fatigue protocol used in the current study. Our study design only allowed for nine-minute windows in the post-test session due to the duration required to complete the BTrackS Balance Test, AccWalker, RPE, and NASA-TLX assessments. Thus, our data supports the Benedict et al. (2017) findings, but their study had a shorter time resolution to identify when the BTrackS Balance Test returned to pre-fatigue levels. A unique contribution of the current study is the inclusion of the NASA-TLX, as Benedict et al. (2017) only included RPE as a perceived fatigue assessment. The observation that the NASA-TLX remained elevated in the 9-18 minute and 18-27-minute windows, during which time the BTrackS Balance Test returned to pre-fatigue levels, suggests that perceived workload and static postural control on a forceplate may fluctuate independently.

Perhaps the most interesting finding was no significant changes in AccWalker postural control measures. It is important to note the AccWalker uses stride time SD and peak flexion SD as the metrics for postural control, whereas the BTrackS Balance Test which uses center of pressure movement. Thus, there is a fundamental difference in the movement characteristics derived from each test. The tests also differ in task difficulty, where the BTrackS Balance Test is a static postural control test and AccWalker is a dynamic postural control task. Both tests have been shown to be valid/reliable (Goble et al., 2018; O'Connor, Baweia, & Goble, 2016; Kuznetzov et al., 2018), resistant to practice effects (Hearn, Levy, Bawaeja, & Goble, 2018; Kuznetsov et al., 2018), and shown to have clinical utility in identifying balance changes after head trauma (Goble et al., 2016; Rhea et al., 2017). While performance on the BTrackS Balance Test has been shown to return to pre-fatigue levels within five minutes (Benedict et al., 2017), this presents a challenge in athletic populations who may need a more immediate assessment of postural control after physical exertion. An objective test of neuromotor performance that has appropriate clinical sensitivity and is not affected by perceived fatigue would be desirable for clinicians who work with athletic populations. The findings of the current study suggest AccWalker fits within those constraints, as the two variables previously shown to change after head trauma (stride time SD and thigh flexion SD) (Rhea et al., 2018) did not change after the fatiguing protocol used in this study. This is a desirable outcome, suggesting that a change in AccWalker performance is likely due to neurosensory mechanisms and not from perceived fatigue.

The second hypothesis explored whether the magnitude of the increased in perceived fatigue scaled with the change in postural control. The findings suggest that this is not the case, with the exception of thigh flexion SD in the head shake condition with the NASA-TLX. The head shake condition has been anecdotally reported as more difficult than the eyes closed condition in the current and previous studies, which may account for the positive association between these two metrics. This observation highlights the role of perceived workload in physical tasks, which may help increase the sensitivity of identifying neuromotor dysfunction in some clinical populations. The positive association between AccWalker stride time SD in the eyes open and head shake conditions suggest that both of these metrics are similarly affected by perceived fatigue, albeit rather minimally due to the observations from hypothesis one.

There were a few limitations of this study, first there was no measure of fatigue or workload immediately after the fatigue protocol. This would have allowed for a measure of perceived fatigue at the time subject finished the fatigue portion rather than after the first set of postural control measures—around 9 minutes post-fatigue. Given the first postural control test (BtrackS or AccWalker) occurred immediately after fatigue, this may have provided a more representative amount of perceived exertion or workload for the first post-test. Second, some subjects mentioned verbally to the lead investigator they felt the head-shake task became easier with each administration. This supports the previous observation that a small learning effect is expected between the first and second administration of the head shake condition (Kuznetsov et al., 2018). Thus, while the fatigue protocol was expected to increase the SD of the AccWalker variables, the fact that the first post-test was the second administration of the test suggest that the expected increase in SD may have been negated by a decrease in SD from the learning effect. The learning effect was minimized by providing a practice trial before the pre-test.

Nevertheless, it may have reduced AccWalker's ability to identify fatigue effects. This observation is tempered by the lack of change in the eyes closed condition after fatigue, which was not shown to have a learning effect from the first to second administration of AccWalker (Kuznetsov et al., 2018). Thus, it is likely that any learning effects played a rather minimal factor in the performance on the AccWalker test. Lastly, the post-test window duration that was required to complete the two postural control tests and the two perceived fatigue tests was larger than previous research who explored similar questions. Specifically Fox et al. (2008) used 3-5 min windows and Benedict et al. (2017) used 5 minute windows. The 9 minute windows used in this study reduced our ability to precisely identify when perceived fatigue began to have a lesser effect on postural control.

In conclusion, the BTrackS Balance Test and perhaps the AccWalker provide clinicians a way to objectively measure postural control, which builds upon previously developed subjective tests used in this context. The data show that perceived fatigue and workload acutely affect the BTrackS Balance Test, but not AccWalker. It may be that the AccWalker is not sensitive enough to changes in postural control to detect the deficits that occur. It is also possible that a more details analysis will show the changes in postural control differ fatigue and other neurosensory perturbations such as a TBI. It is our hope that future research will use this study in order to better distinguish the changes in postural control that occur in various settings; such as fatigue. We hope these findings will help clinicians working with civilian, military, and athletic communities better select the test most appropriate for them based on their desired assessment characteristics (static or dynamic balance) and administration time relative to physical exertion. It should be noted that the BTrackS Balance Test is already an FDA-approved Class 1 Medical Device available to the public, whereas the AccWalker smartphone app is under development and only available by contacting Dr. Rhea.

CHAPTER V

EXECUTIVE SUMMARY

Postural control is a complex and dynamic process that is further complicated by ever changing individual characteristics and environmental factors. For example, even when attempting the simple task of standing still, the postural control system must adjust the body to account for internal (e.g., respiration) and external (e.g., gravity) perturbations. These postural adjustments can be more difficult if fatigue is present, which can delay the timing or reduce the magnitude of the postural adjustment. However, the extent to which fatigue influences postural control is not well understood. This is a challenge because balance tests are becoming more commonly adopted in the civilian and military athletic communities to characterize neuromotor control after head trauma or other neurological changes. Thus, there is a need to better understand how fatigue effects performance in a variety of postural control tasks in order to better interpret data from these balance tests. The purpose of this study was to measure postural control with objective balance assessments before and after a standardized fatigue protocol. It was hypothesized that (1) a decline in postural control would be observed immediately after the fatigue protocol but would return to baseline levels after 9 minutes and (2) the magnitude of the immediate postural control decline would be associated with an individual's level of perceived fatigue. Two hypotheses were tested. Hypothesis one stated that a decline in postural control would be observed immediately after the fatigue protocol but will return to baseline levels after 9 minutes. RPE was elevated up to 27 minutes after the fatigue protocol, and NASA-TLX was elevated up to 9 minutes after the fatigue protocol. Data from the BtrackS supported hypothesis one, however AccWalker data showed no significant changes after the fatigue test. Hypothesis two stated the magnitude of the immediate postural control decline would be associated with an individual's level of perceived fatigue. Data from only one pair of variables (NASA-TLX and AccWalker thigh flexion SD) provided support for this hypothesis. While similar perceived fatigue was observed acutely, the manner in which perceived physical fatigue (indexed by RPE) and perceived workload (indexed by NASA-TLX) recover appear to be at different rates after the fatigue protocol.

In conclusion, the overall data showed that the BtrackS is acutely affected by perceived fatigue, but AccWalker showed no changes in performance after the fatigue protocol. Based on the results of this study, future research should consider that workload, that includes the cognitive energy cost of achieving a task, recovers faster than RPE; the physiological cost of a task.

REFERENCES

Adkin, A. L., Frank, J. S., Carpenter, M. G., & Peysar, G. W. (2000). Postural control is scaled to level of postural threat. *Gait & Posture, 12*(2), 87-93.

Baloh R.W., Fife, T.D., Zwerling, L., Socotch T., Jacobson, K., Bell, T., & Beykirch, K. (1994). Comparison of static and dynamic posturography in young and older normal people. *Journal of the American Geriatrics Society, 42*(4),405-441.

Bell, D. R., Guskiewicz, K. M., Clark, M. A., & Padua, D. A. (2011). Systematic review of the balance error scoring system. *Sports Health, 3*(3), 287-295.

Bellew, J. W., Panwitz, B. L., Peterson, L., Brock, M. C., Olson, K. E., & Staples, W. H. (2009). Effect of acute fatigue of the hip abductors on control of balance in young and older women. *Archives of Physical Medicine and Rehabilitation, 90*(7), 1170-1175.

Benedict, S. E., Hinshaw, J. W., Fields, R. B., Baweja, H. S., & Goble, D. J. (2017). Effects of fatigue on the BTrackS balance test for concussion management. *International Journal of Athletic Therapy and Training, 22*(4), 23-28.

Berg, K., & Norman, K. E. (1996). Functional assessment of balance and gait. *Clinics in Geriatric Medicine, 12*(4), 705-723.

Berg, K., Wood-Dauphinee, S., & Williams, J. I. (1995). The Balance Scale: reliability assessment with elderly residents and patients with an acute stroke. *Scandinavian Journal of Rehabilitation Medicine, 27*, 1, 27-36.

Bigland-Ritchie, B., & Woods, J. J. (January 01, 1984). Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle & Nerve,* 7, 9.

Bird, M.-L., Pittaway, J. K., Cuisick, I., Rattray, M., & Ahuja, K. D. K. (2013). Age-related changes in physical fall risk factors: Results from a 3 year follow-up of community dwelling older adults in Tasmania, Australia. *International Journal of Environmental Research and Public Health, 10*(11), 5989–5997.

Bisson, E.J., Mcewen, D., Lajoie, Y., & Bilodeau, M. (2011). Effects of ankle and hip muscle fatigue on postural sway and attentional demands during unipedal stance. *Gait & Posture,33*(1), 83-87.

Borg, G. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise, 14*(5), 377-381.

Boulos, M.N.K., Brewer, A.C., Karimkhani, C., Buller, D.B.,& Dellavalle, R.P. (2014) Mobile medical and health apps: State of the art, concerns, regulatory control and certification. *Online Journal of Public Health Informatics, 5*(3):229

Broglio, S.P., Guskiewicz, K.M., & Norwig, J. (2017). If you're not measuring, you're guessing: The advent of objective concussion assessments. *Journal of Athletic Training, 52*(3), 160-166

Buckley, T.A., Oldham, J.R., & Caccese, J.B. (2016). Postural control deficits identify lingering post-concussion neurological deficits. *Journal of Sport and Health Science, 5*(1), 61-69.

Cavanaugh, J.T., Guskiewicz, K.M., & Stergiou, N. (2006). A nonlinear dynamic approach for evaluating postural control. *Sports Medicine, 35*(11), 935-950.

Cavanaugh, J.T., Guskiewicz, K.M., Giuliani, C., Marshall, S., Mercer, V.S., & Stergiou, N. (2006). Recovery of postural control after cerebral concussion: New insights using approximate entropy. *Journal of Athletic Training, 41*(3), 305-313.

Chang, J.O., Levy, S.S., Seay, S.W., & Goble, D.J. (2014). An alternative to the balance error scoring system: Using a low-cost balance board to improve the validity/reliability of sports-related concussion balance testing. *Clinical Journal of Sport Medicine, 24*(3), 256-262.

Chen, M. J., Fan, X., & Moe, S.T. (2002). Criterion-related validity of the Borg ratings of perceived exertion scale in healthy individuals: A meta-analysis. *Journal of Sports Sciences,20*(11), 873-899.

Claudino, R., dos, S.E.C., & Santos, M.J. (2013). Compensatory but not anticipatory adjustments are altered in older adults during lateral postural perturbations. *Clinical Neurophysiology, 124*(8), 1628-37.

Collins, J.J., Luca, C.J., Burrows, A., & Lipsitz, L.A. (1995). Age-related changes in open-loop and closed-loop postural control mechanisms. *Experimental Brain Research, 104*(3), 480-492.

Costa, M., Priplata, A.A., Lipsitz, L.A., Wu, Z., Huang, N.E., Goldberger, A.L., & Peng, C.K. (2007). Noise and poise: Enhancement of postural complexity in the elderly with a stochastic-resonance–based therapy. *Europhysics Letters, 77*(6), 68008.

Crowder, T.A., Ferrara, A.L., & Levinbook, M.D. (2013). Creation of a criterion-referenced military optimal performance challenge. *Military Medicine, 178*(10), 1085-1101.

Delignières, D., Torre, K., & Bernard, P.L. (2011). Transition from persistent to anti-persistent correlations in postural sway indicates velocity-based control. *PLoS Computational Biology, 7(*2), e1001089.

Derave, W., Tombeux, N., Cottyn, J., Pannier, J. L., & De, C. D. (January 01, 2002). Treadmill Exercise Negatively Affects Visual Contribution to Static Postural Stability. *Int J Sports Med*, *23*, 1, 44-49.

Di, G.I., Maganaris, C.N., Baltzopoulos, V., & Loram, I.D. (2009). The proprioceptive and agonist roles of gastrocnemius, soleus and tibialis anterior muscles in maintaining human upright posture. *The Journal of Physiology, 587*, 2399-2416

Diekfuss, J. A., Ward, P., & Raisbeck, L. D. (2017). Attention, workload, and performance: A dual-task simulated shooting study. *International Journal of Sport and Exercise Psychology, 15*(4), 423-437

Finnoff, J.T., Peterson, V.J., Hollman, J.H., & Smith, J. (2009). Intrarater and interrater reliability of the Balance Error Scoring System (BESS). *PM&R, 1*(1), 50-54.

Fino, P.C. (2016). A preliminary study of longitudinal differences in local dynamic stability between recently concussed and healthy athletes during single and dual-task gait. *Journal of Biomechanics, 49*(9), 1983-1988.

Forestier, N., Teasdale, N., & Nougier, V. (2002). Alteration of the position sense at the ankle induced by muscular fatigue in humans. *Medicine & Science in Sports & Exercise, 34*(1), 117-122.

Fox, Z.G., Mihalik, J.P., Blackburn, J.T., Battaglini, C.L., & Guskiewicz, K.M. (2008). Return of postural control to baseline after anaerobic and aerobic exercise protocols. *Journal of Athletic Training*, *43*(5), 456-63.

Gaerlan, M.G., Alpert, P.T., Cross, C., Louis, M., & Kowalski, S. (2012). Postural balance in young adults: The role of visual, vestibular and somatosensory systems. *Journal of the American Academy of Nurse Practitioners*, *24*(6), 375-381.

Gago, M.F., Yelshyna, D., Bicho, E., Silva, H.D., Rocha, L., Rodrigues, M L., & Sousa, N. (2016). Compensatory postural adjustments in an Oculus virtual reality environment and the risk of falling in Alzheimer's disease. *Dementia and Geriatric Cognitive Disorders Extra*, *6*(2), 252-267.

Goble, D., Manyak, K.A., Abdenour, T.E., Rauh, M.J., & Baweja, H.S. (2016). An initial evaluation of the BTrackS Balance Plate and Sports Balance software for concussion diagnosis. *International Journal of Sports Physical Therapy, 11*(2), 149.

Guskiewicz, K.M., Ross, S.E., & Marshall, S. (2001). Postural stability and neuropsychological deficits after concussion in collegiate athletes. *Journal of Athletic Training*, *36*(3), 263.

Guskiewicz, K. M. (2011). Balance assessment in the management of sport-related concussion. *Clinics in Sports Medicine, 30*(1), 89-102

Hart, S. G. (2006). Nasa-Task Load Index (NASA-TLX); 20 Years Later. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 50*, 9, 904-908.

Hearn, M. C., Levy, S. S., Baweja, H. S., & Goble, D. J. (2018). BTrackS Balance Test for Concussion Management is Resistant to Practice Effects. *Clinical Journal of Sport Medicine, 28*(2), 177-179.

Hunt, T.N., Ferrara, M.S., Bornstein, R.A., & Baumgartner, T.A. (2009). The reliability of the modified balance error scoring system. *Clinical Journal of Sport Medicine*, *19*(6), 471-475.

Inness, E.L., Howe, J., Niechwiej-Szwedo, E., Jaglal, S.B., McIlroy, W.E., & Verrier, M.C. (2011). Measuring balance and mobility after traumatic brain injury: Validation of the Community Balance and Mobility Scale (CB&M). *Physiotherapy Canada, 63*(2), 199-208.

Iverson, G.I. & Koehle, M.S. (2013). Normative data for the balance error scoring system in adults, *Rehabilitation Research and Practice,* 846418.

Jeka, J., Kiemel, T., Creath, R., Horak, F.B., & Peterka, R. (2004). Controlling human upright posture: Velocity information is more accurate than position or acceleration. *Journal of Neurophysiology, 92*(4), 2368-2379.

Johnston, R.B., Howard, M.E., Cawley, P.W., & Losse, G.M. (1998). Effect of lower extremity muscular fatigue on motor control performance. *Medicine & Science in Sports & Exercise,30*(12), 1703-1707.

Kuznetsov N.A., Robins R.K., Jakiela, J.T., Long, B., Wright, W.G., Ross, S.E., Haran, F.J., & Rhea, C.K. (und2018) Validity and reliability of a portable tool for measuring dynamic balance. *Physiological Measurement*, 39, 02NT01

Laughton, C.A., Slavin, M., Katdare, K., Nolan, L., Bean, J.F., Kerrigan, D., Phillips, E., Lipsitz, L.A., & Collins, J.J. (2003). Aging, muscle activity, and balance control: Physiologic changes associated with balance impairment. *Gait & Posture, 18*(2), 101-108.

Majumdar, D., Pal, M. S., & Majumdar, D. (2010). Effects of military load carriage on kinematics of gait. *Ergonomics*, *53*(6), 782-791.

Manor, B., Costa, M.D., Hu, K., Newton, E., Starobinets, O., Kang, H.G., Novak, V., & Lipsitz, L.A. (2010). Physiological complexity and system adaptability: Evidence from postural control dynamics of older adults. *Journal of Applied Physiology, 109*(6), 1786-1791.

McCrea, M., Guskiewicz, K.M., Marshall, S.W., Barr, W., Randolph, C., Cantu, R.C., Onate, J.A., Yang, J., & Kelly, J.P. (2003). Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. *JAMA, 290*(19), 2556-2563.

Mehta, R.K. & Agnew, M.J. (2014). Subjective evaluation of physical and mental workload interactions across different muscle groups. *Journal of Occupational and Environmental Hygiene, 12*(1), 62-68.

Melzer, I., Benjuya, N., & Kaplanski, J. (2004). Postural stability in the elderly: A comparison between fallers and non-fallers. *Age and Ageing, 33*(6), 602-607

National Council on Ageing. (2005). Falls among older adults: risk factors and prevention strategies. In *Fall free: promoting a national falls prevention action plan*. J.A. Stevens Eds.

Oie, K.S., Kiemel, T., & Jeka, J.J. (2002). Multisensory fusion: Simultaneous re-weighting of vision and touch for the control of human posture. *Cognitive Brain Research, 14*(1), 164-176.

Paillard, T. (2012). Effects of general and local fatigue on postural control: A review. *Neuroscience & Biobehavioral Reviews, 36*(1), 162-176.

Patterson, J.A., Amick, R.Z., Pandya, P.D., Hakansson, N., & Jorgensen, M.J. (2014). Comparison of a mobile technology application with the Balance Error Scoring System. *International Journal of Athletic Therapy and Training, 19*(3), 4-7

Patterson, J.A., Amick, R.Z., Thummar, T., & Rogers, M.E. (2014), Validation of measures from the smartphone sway balance application: A pilot study. *International Journal of Sports Physical Therapy, 9*(2), 135-139.

Patton, J.F., Morgan, W.P., & Vogel, J.A. (1977). Perceived exertion of absolute work during a military physical training program. *European Journal of Applied Physiology and Occupational Physiology, 36*(2), 107-114.

Peterka, R.J. (2002). Sensorimotor integration in human postural control. *Journal of Neurophysiology, 88*(3), 1097-1118.

Pletcher, E.R., Williams, V.J., Abt, J.P., Morgan, P.M., Parr, J.J., Wohleber, M.F., Lovalekar, M., & Sell, T.C. (2017). Normative data for the NeuroCom Sensory Organization Test in US Military Special Operations Forces. *Journal of Athletic Training, 52*(2), 129-136.

Powers, K.C., Kalmar, J.M., & Cinelli, M.E. (2014). Recovery of static stability following a concussion. *Gait & Posture, 39*(1), 611-614.

Raisbeck, L. D., Diekfuss, J. A., Wyatt, W., & Shea, J. B. (December 01, 2015). Motor imagery, physical practice, and memory: The effects on performance and workload. *Perceptual and Motor Skills, 121*(3), 691.

Raisbeck, L. D., & Diekfuss, J. A. (2015). Fine and gross motor skills: The effects on skill-focused dual-tasks. *Human Movement Science, 43*, 146-154

Raisbeck, L. D., & Diekfuss, J. A. (2017). Verbal Cues and Attentional Focus: A Simulated Target-Shooting Experiment. *Journal of Motor Learning and Development, 5*(1), 148-159

Ramdani, S., Seigle, B., Lagarde, J., Bouchara, F., & Bernard, P.L. (2009). On the use of sample entropy to analyze human postural sway data. *Medical Engineering & Physics, 31*(8), 1023-1031.

Rehan Youssef, A., & Gumaa, M. (2017). Validity and reliability of smartphone applications for clinical assessment of the neuromusculoskeletal system. *Expert Review of Medical Devices, 14*(6), 481-493.

Rhea, C.K., Kuznetsov, N.A., Robins, R.K., Jakiela, J.T., LoJacono, C.T., Ross, S.E., MacPherson, R.P., Long, B., Haran, F.J., & Wright, W.G. Dynamic balance decrements last longer than 10 days following a concussion. *International Society of Posture & Gait Research,* Ft. Lauderdale, FL, 2017

Rhea, C.K., Kuznetsov, N.A., Ross, S.E., Long, B., Jakiela, J.T., Bailie, J.M., Yanagi, M.A., Haran, F.J., Wright, W.G., Robins, R.K., Sargent, P.D., & Duckworth, J.L. (2017) Development of a portable tool for screening neuromotor sequelae from repetitive low-level blast exposure. *Military Medicine, 182*(3/4):147-154

Rhea, C.K., Silver, T.A., Hong, S.L., Ryu, J.H., Studenka, B.E., Hughes, C.M.L., & Haddad, J.M. (2011). Noise and complexity in human postural control: Interpreting the different estimations of entropy. *PLOS ONE, 6*(3): e17696

Rhea, C.K., Kuznetsov, N.A., Jakiela, J.T., Ross, S.E., Wright, W.G., Haran, F.J., Graves, W., Bailie, J.M., Yanagi, M.A., & Duckworth, J.L. Longitudinal tracking of neuromotor performance after repeated sub-concussive blast exposure using a custom smartphone app. *Military Health System Research Symposium*, Kissimmee, FL, August 2018, national conference, under review

Riach, C., & Starkes, J. (1994). Velocity of centre of pressure excursions as an indicator of postural control systems in children. *Gait & Posture, 2*(3), 167-172.

Riemann, B.L., Guskiewicz, K.M., & Shields, E.W. (1999). Relationship between clinical and forceplate measures of postural stability. *Journal of Sport Rehabilitation, 8*(2), 71-82.

Rietdyk, S., Patla, A.E., Winter, D.A., Ishac, M.G., & Little, C.E. (1999). Balance recovery from medio-lateral perturbations of the upper body during standing. *Journal of Biomechanics, 32*(11), 1149-1158.

Saladin, K.S. (2012). *Anatomy & physiology the unity of form and function* (6th ed.). New York, NY: McGraw-Hill. P. 424

Schneiders, A.G., Sullivan, S.J., Handcock, P., Gray, A., & McCrory, P.R. (2012). Sports concussion assessment: The effect of exercise on dynamic and static balance. Scandinavian *Journal of Medicine and Science, 22*(1), 85-90.

Sefton, J.E.M., Hicks-Little, C.A., Hubbard, T.J., Clemens, M.G., Yengo, C.M., Koceja, D.M., & Cordova, M.L. (2009). Sensorimotor function as a predictor of chronic ankle instability. *Clinical Biomechanics, 24*(5), 451-458.

Simpson, R.J., Graham, S.M., Florida-James, G.D., Connaboy, C., Clement, R., & Jackson, A.S. (2010). Perceived exertion and heart rate models for estimating metabolic workload in elite British soldiers performing a backpack load-carriage task. *Applied Physiology, Nutrition, and Metabolism, 35*(5), 650-656.

Slobounov, S., Cao, C., Sebastianelli, W., Slobounov, E., & Newell, K. (2008). Residual deficits from concussion as revealed by virtual time-to-contact measures of postural stability. *Clinical Neurophysiology, 119*(2), 281-289.

Springer, B.K., & Pincivero, D.M. (2009). The effects of localized muscle and whole-body fatigue on single-leg balance between healthy men and women. *Gait & Posture, 30*(1), 50-54.

Stins, J.F., Michielsen, M.E., Roerdink, M., & Beek, P.J. (2009). Sway regularity reflects attentional involvement in postural control: Effects of expertise, vision and cognition. *Gait & Posture, 30*(1), 106-109.

Surenkok, O., Isler, A.K., Aytar, A., Gultekin, Z., & Akman, M.N. (2006). Effect of knee muscle fatigue and lactic acid accumulation on balance in healthy subjects. *Isokinetics and Exercise Science, 14*(4), 301-306.

Vera, J., Jiménez, R., García, J. A., Perales, J. C., & Cárdenas, D. (January 01, 2018). Baseline Intraocular Pressure Is Associated With Subjective Sensitivity to Physical Exertion in Young Males. *Research Quarterly for Exercise and Sport, 89*(1), 25-37.

Vuillerme, N., Nougier, V., & Prieur, J. (2001). Can vision compensate for a lower limbs muscular fatigue for controlling posture in humans? *Neuroscience Letters, 308*(2), 103-106.

Windhorst, U. (2007). Muscle proprioceptive feed and spinal networks. *Brain Res. Bull. 73*, 155-202.

Winter, D.A., Patla, A.E., & Frank, J.S. (1990). Assessment of balance control in humans. *Medical Progress Through Technology, 16*, 1-2.

Zahra, S. M., Lora, A. C., Fadel, M. M., Lin, L., & Amir, B. (September 01, 2017). Effects of Task Type, Task Duration, and Age on Body Kinematics and Subjective Fatigue. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 61*(1), 1040.